



What Drives Curiosity?

Robotics Technologies on the
Mars Science Laboratory

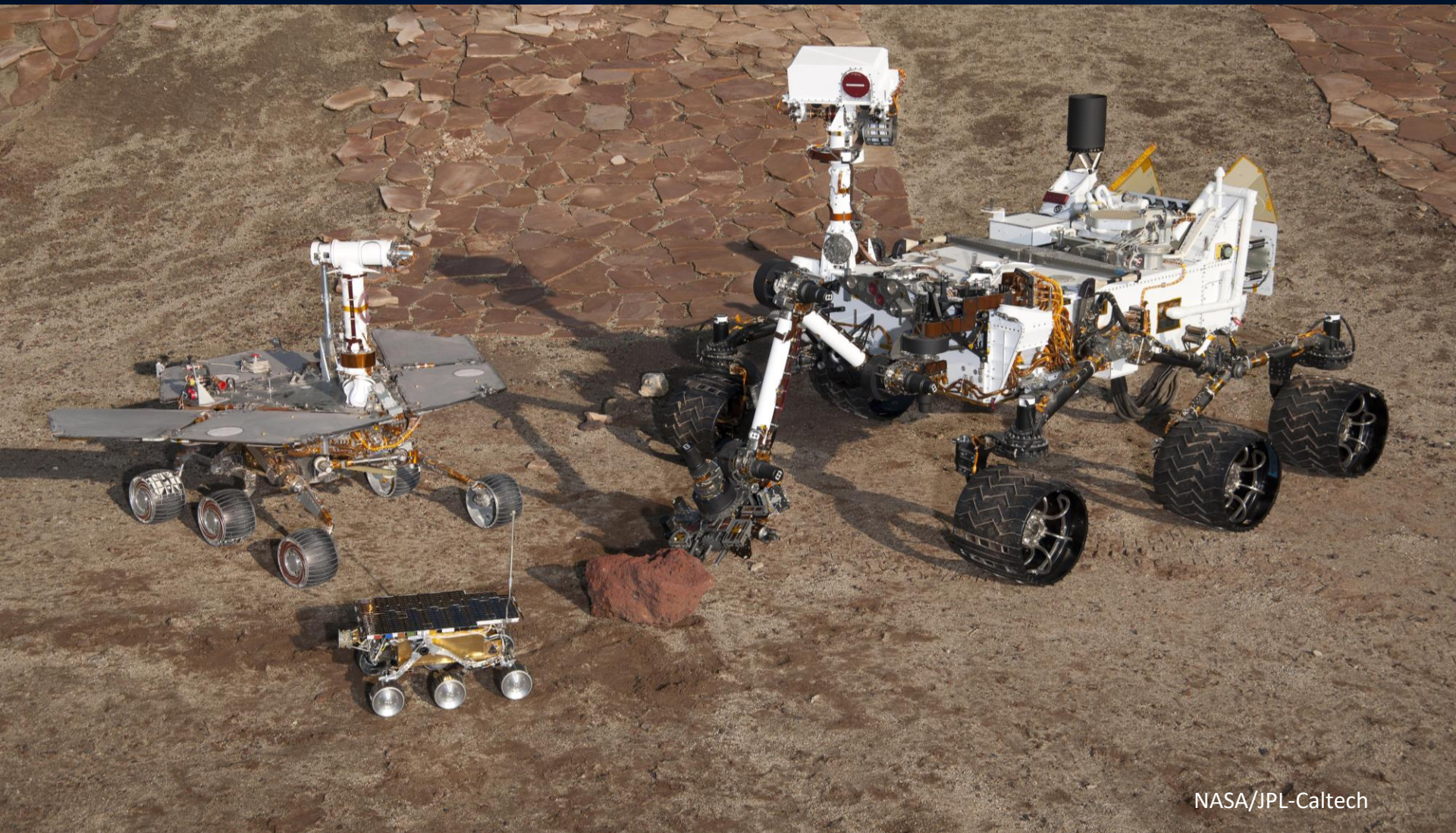
Mark Maimone
Jet Propulsion Laboratory
California Institute of Technology

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Artist's Concept. NASA/JPL-Caltech



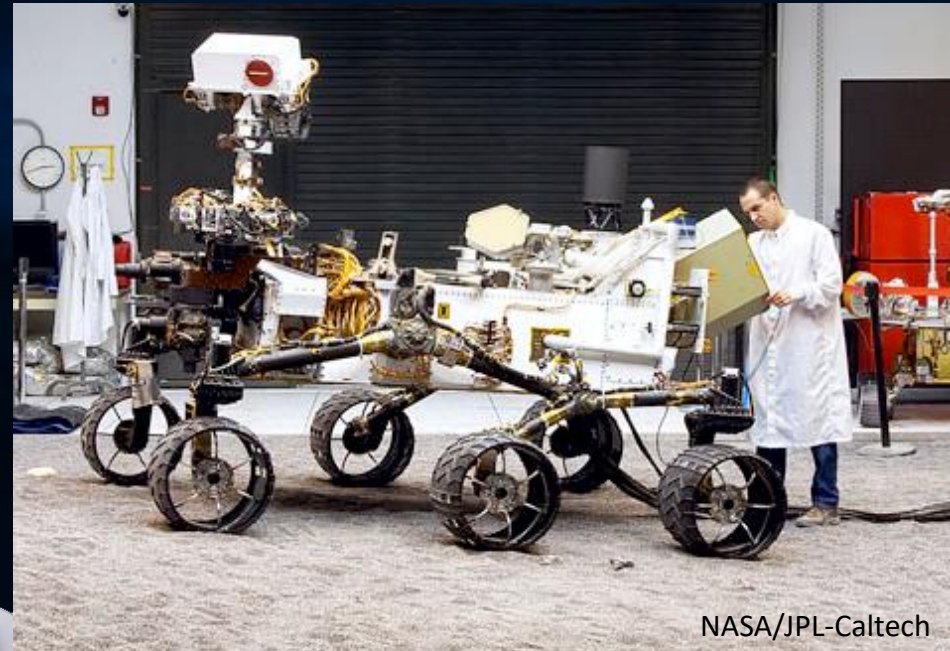
Mars Rover Family Portrait



NASA/JPL-Caltech



WDC? People!

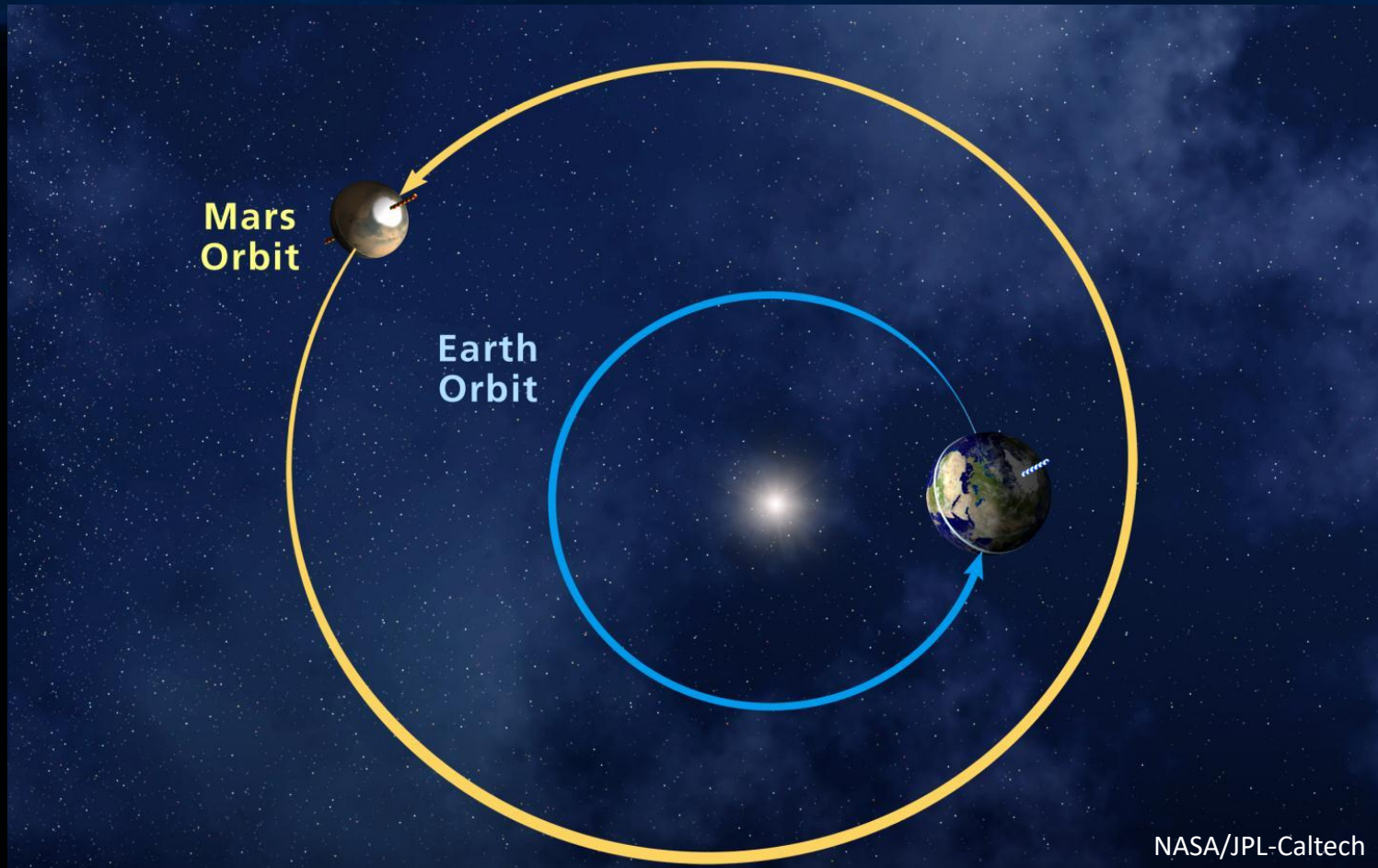


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Because of the distance between Earth and Mars, we can't drive a rover in real time.



It takes between 4 and 22 minutes each way for a signal to travel between the two planets.



Also, Logistics

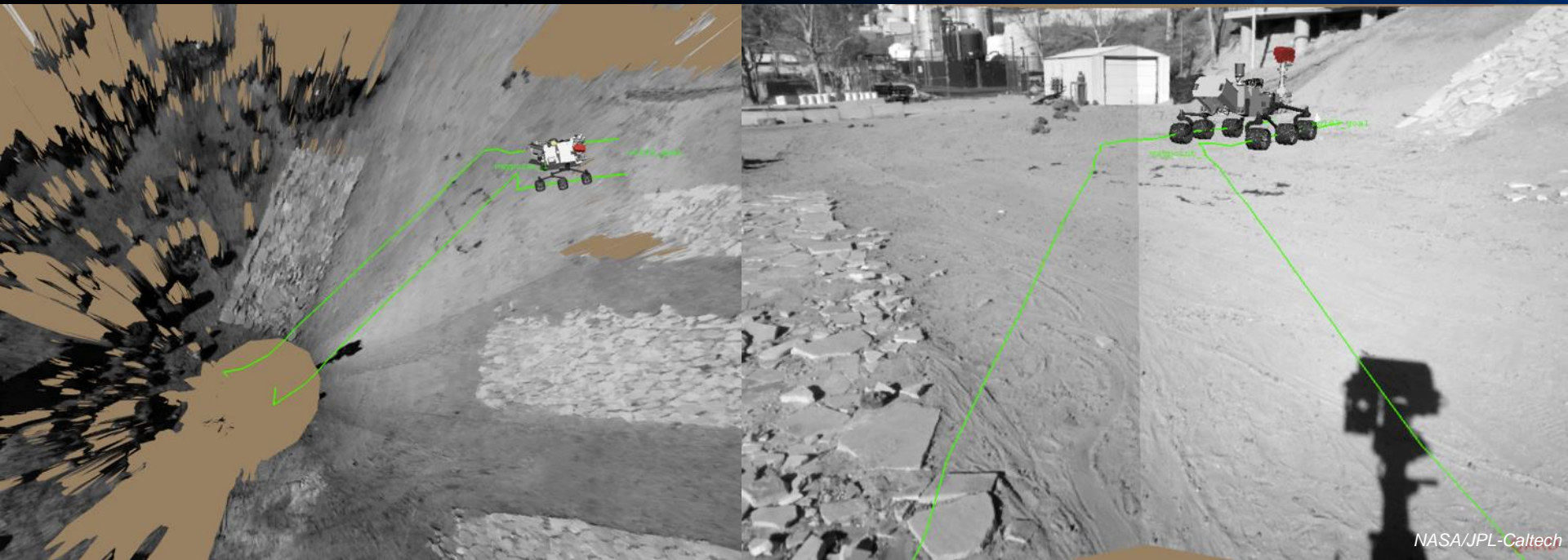
The Deep Space Network is a shared resource for dozens of missions.

We often only get one uplink and few downlink windows each day





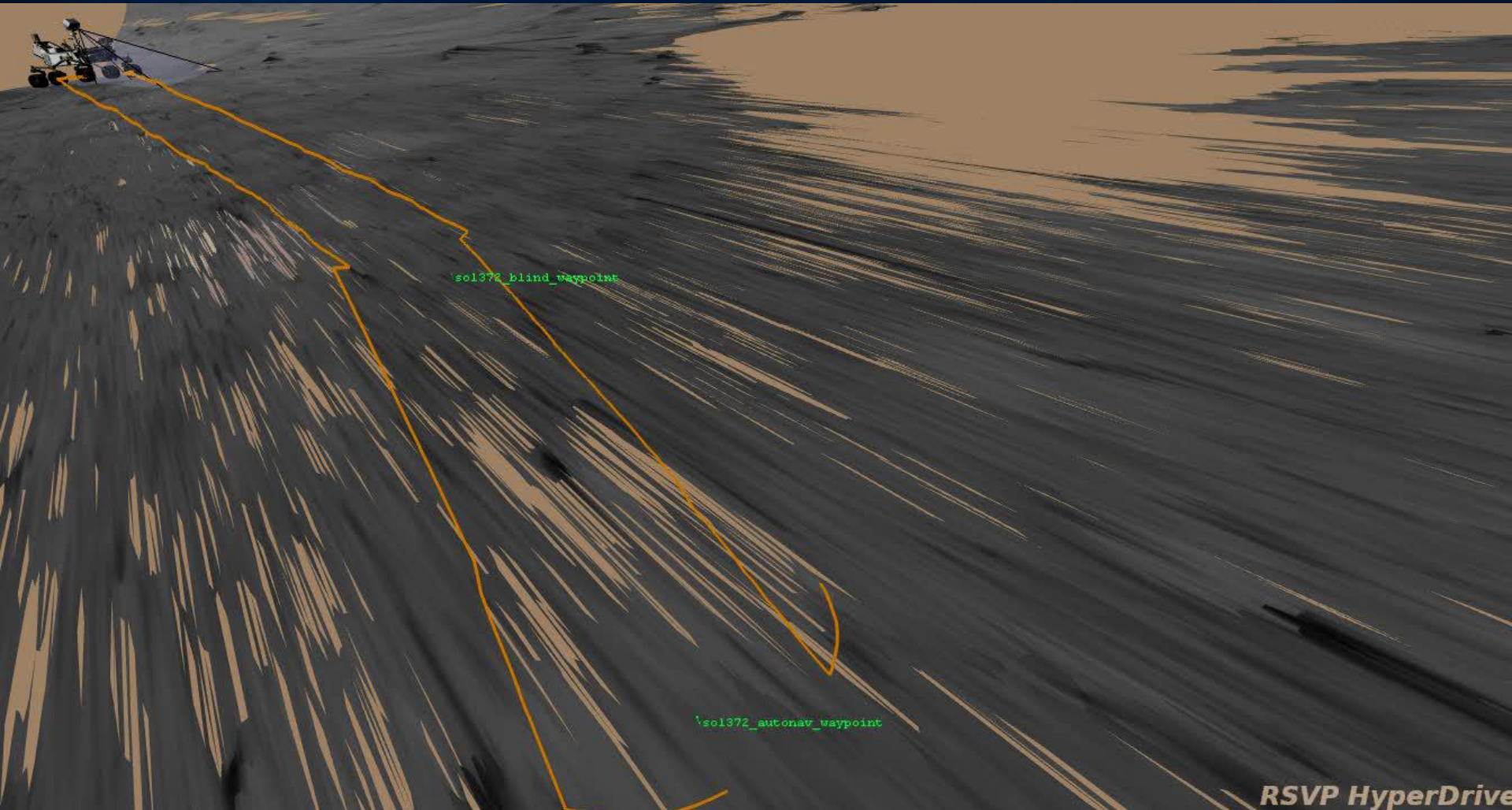
A previous day's images are fed into the Rover Simulation Visualization Program (RSVP) and 3D meshes are created.



Rover drivers wear shuttered 3D goggles to view stereo imagery and 3D meshes



Drives are planned in 3D meshes out to the limit of visibility

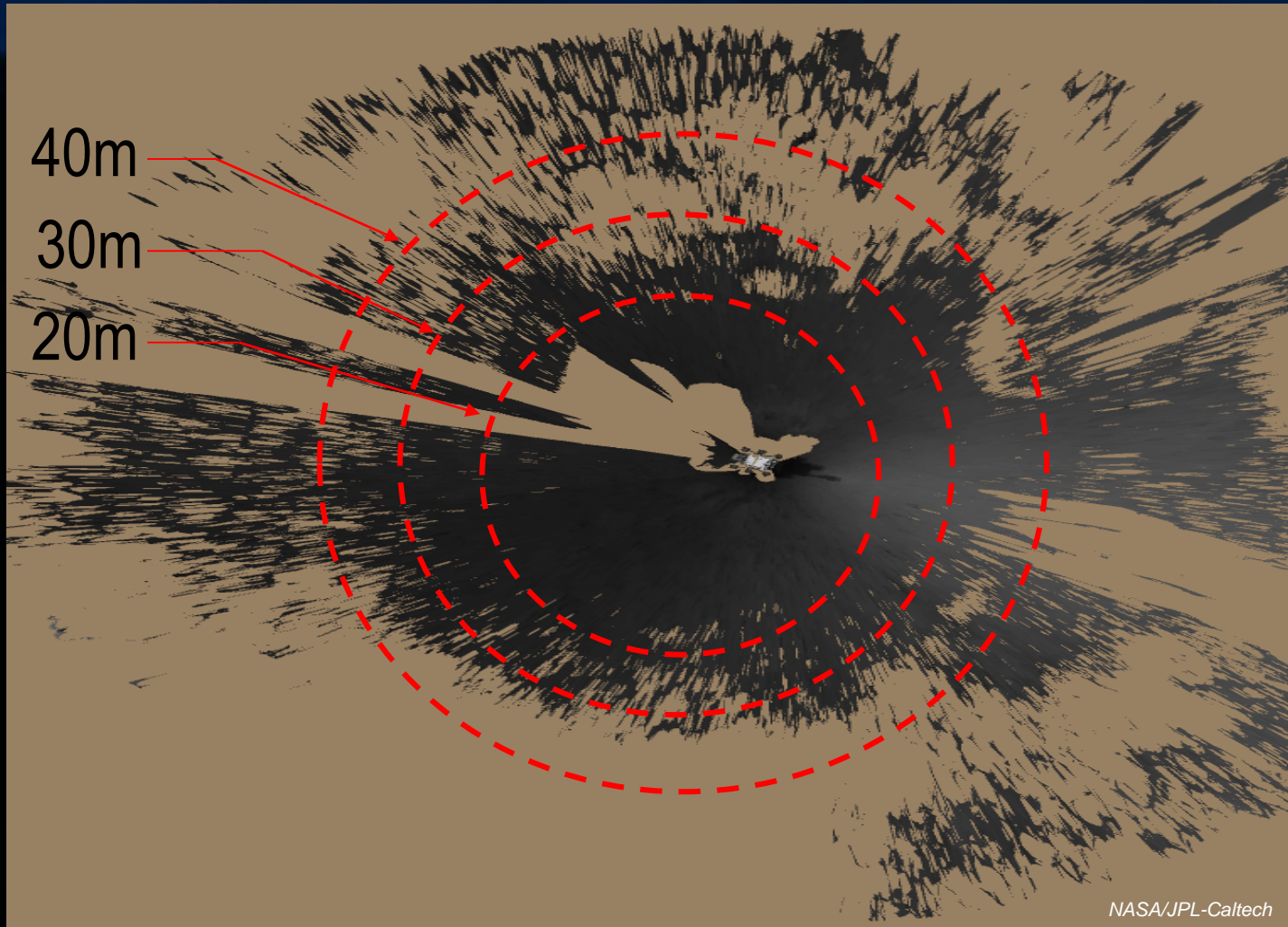


RSVP HyperDrive

NASA/JPL-Caltech



This image shows how much detail the Navcam cameras can typically see nearby.

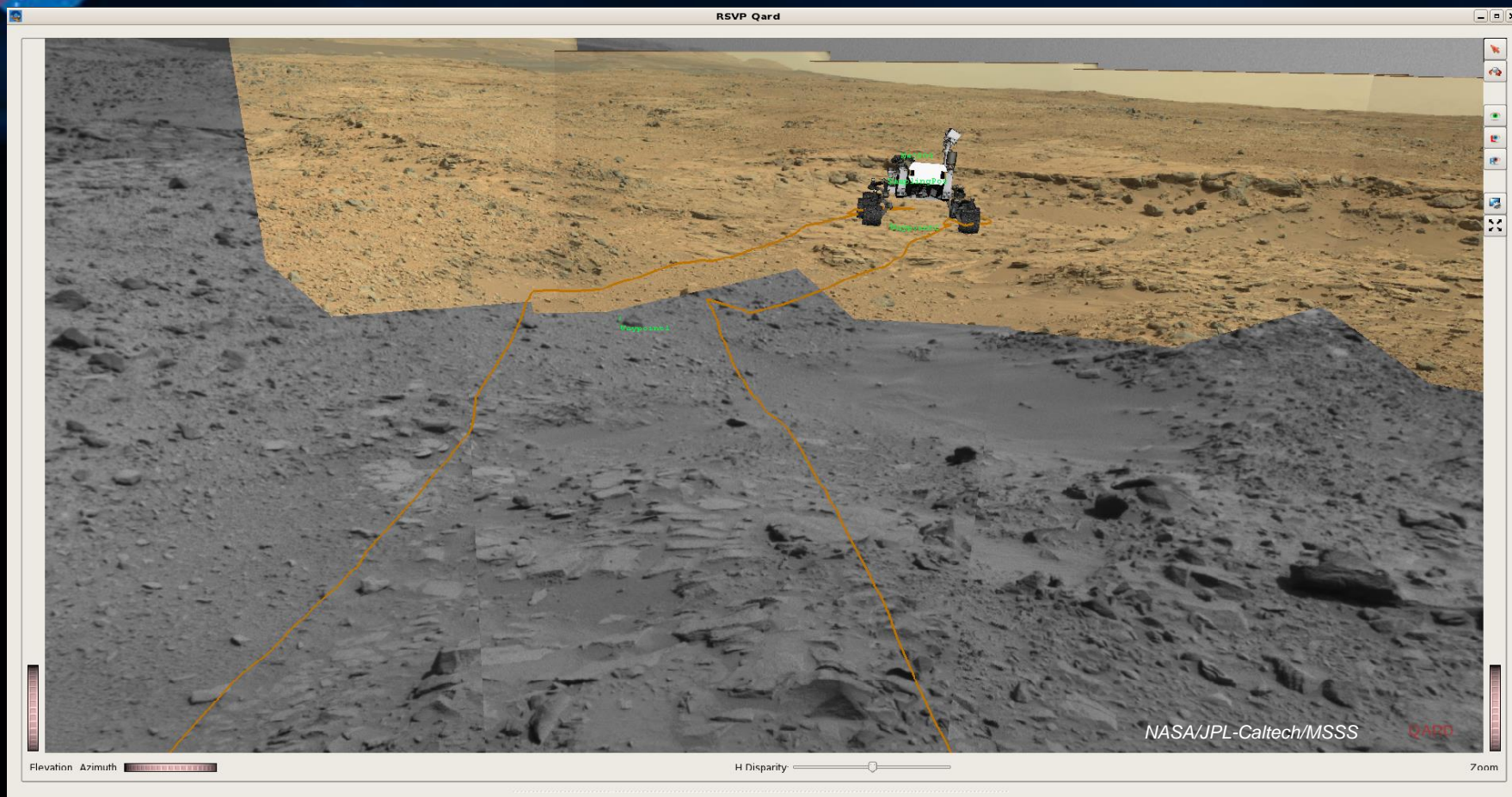


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3D data from Navcam stereo is often supplemented by color texture information in Mastcam images



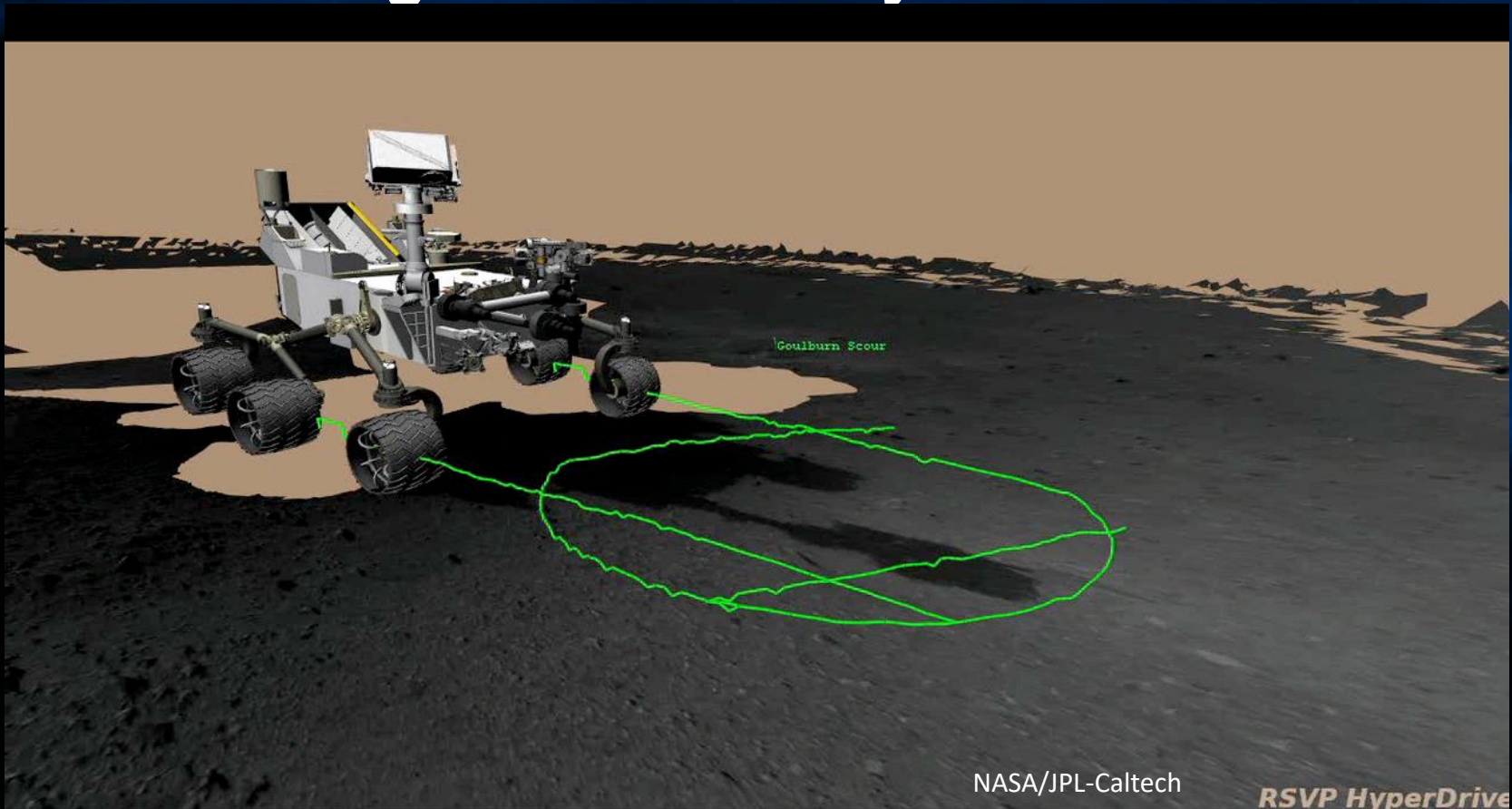
Multiple Drive Views



Drives are simulated on 3D meshes, and can be visualized in many ways. Here a mosaic of Navcam and Mastcam images provide context.



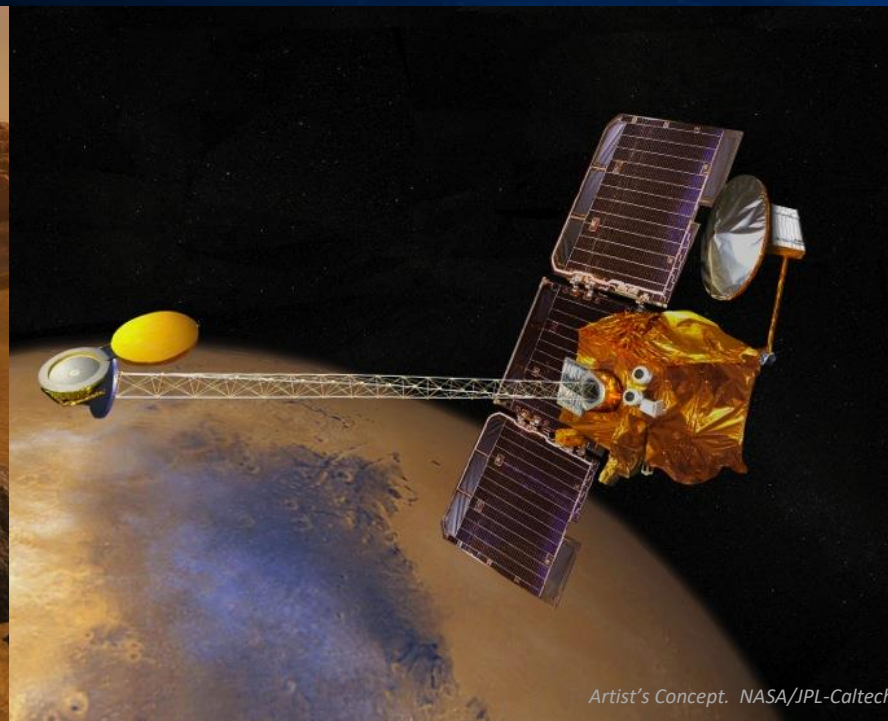
For “directed driving,” drivers command the rover to move a certain distance over ground that they know is safe.



This is the fastest way to drive, because no predictive hazard processing is done, but distance is limited by what people can see. Curiosity will *always* stop the drive if a fault is detected!



Curiosity carries out the activities and then sends data to the orbiters, whose larger antennas relay it to Earth.

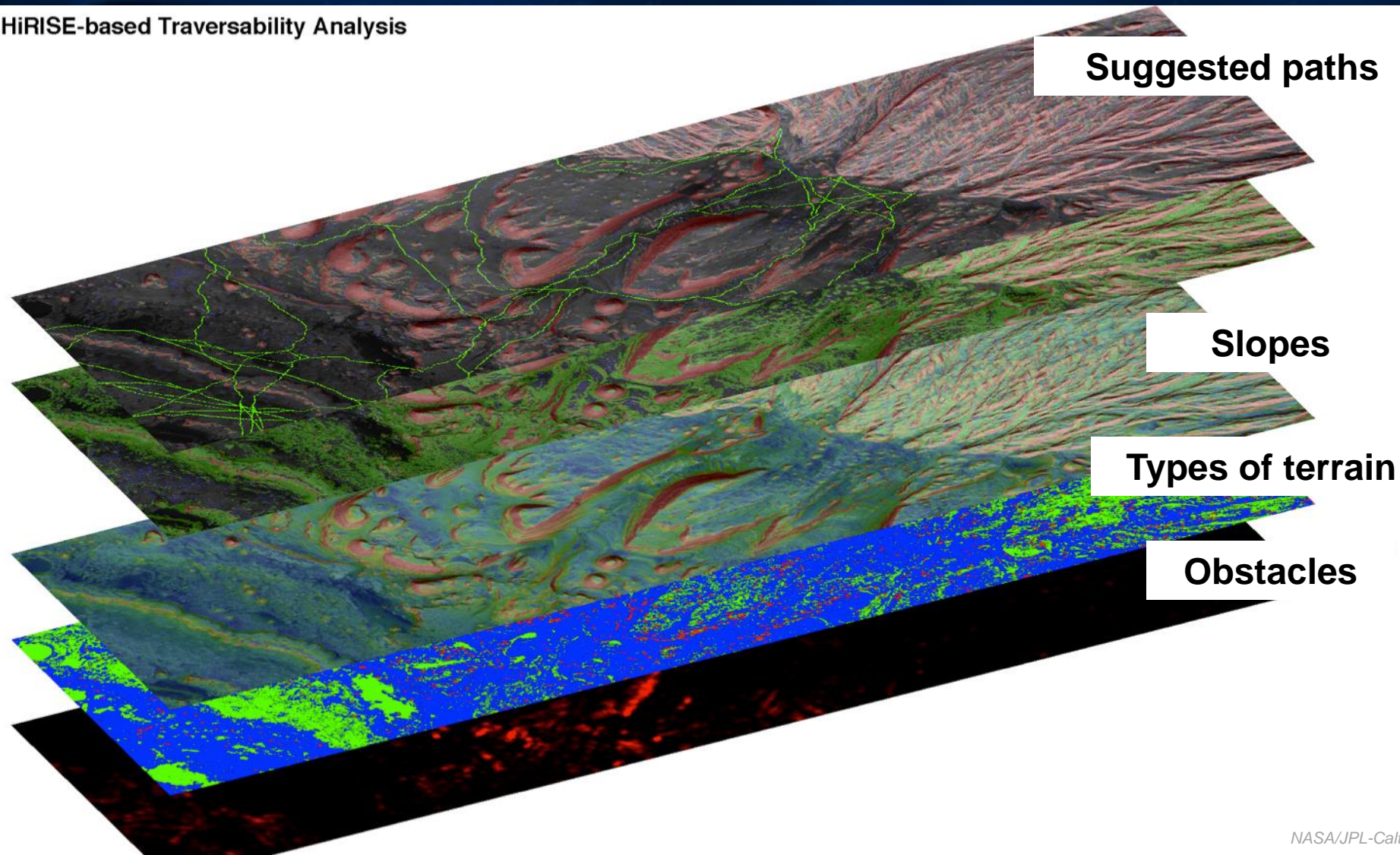


It takes less energy and a smaller antenna to send data 200 miles (322 km) up to an orbiter, rather than millions of miles to Earth, though direct contact is available.



Data from the Mars Reconnaissance Orbiter helps “see” several kilometers ahead, allowing for long term planning.

HiRISE-based Traversability Analysis

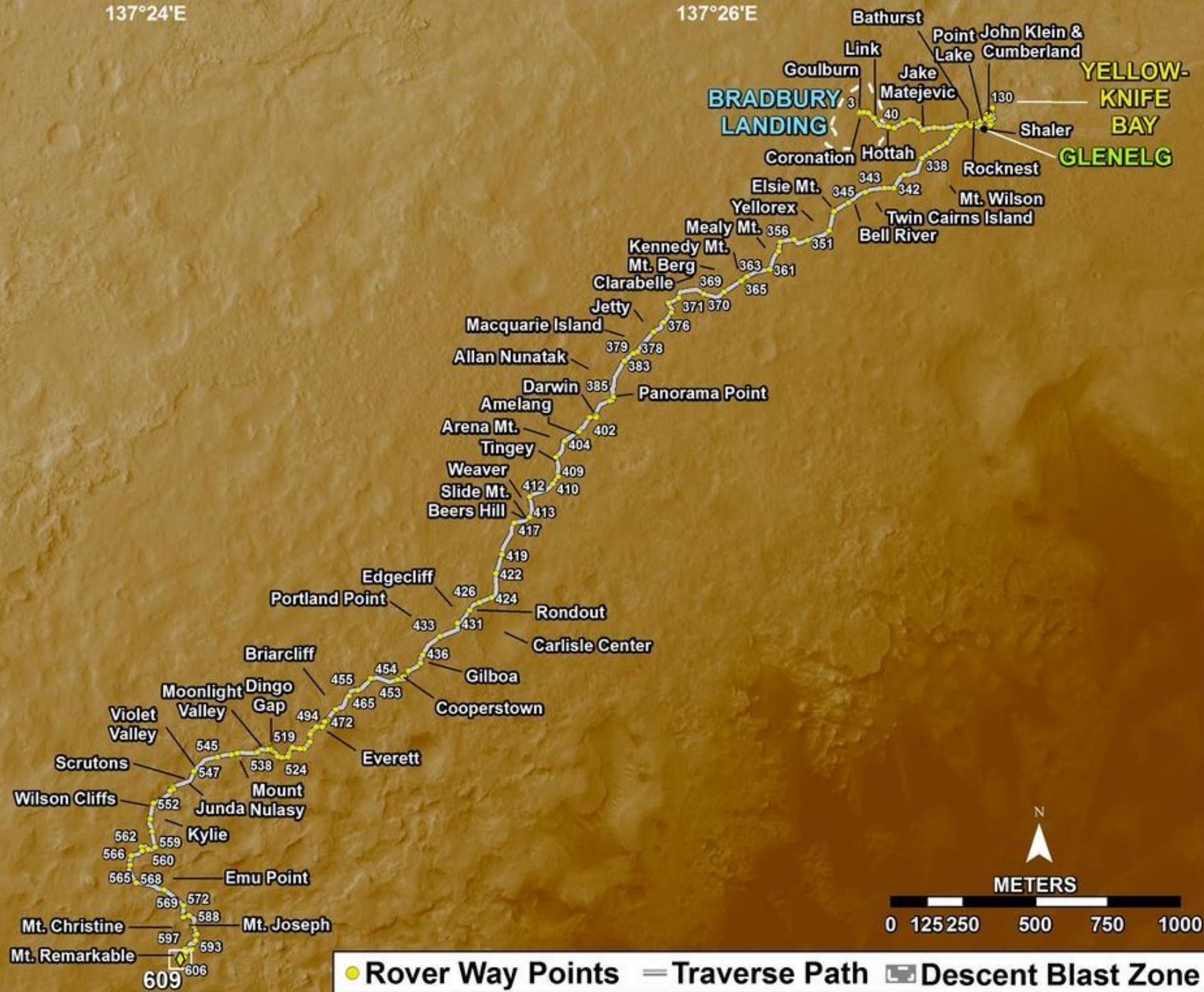


137°24'E

137°26'E

-4°36'S

-4°38'S





WDC? Robotics Tech!

Velocity-controlled Driving
Autonomous Fault Response
Visual Odometry
Dense Stereo Vision
Autonomous Terrain Assessment
Local and Global Waypoint Planning
Multi-sol Driving
Visual Target Tracking
Precision Arm Placement
Percussive Drill
Cached Sample Manipulation
Simulation
Rover Sequencing and Visualization

Artist's Concept. NASA/JPL-Caltech



MSL Robotic Arm Overview



- MSL Arm is ~ 2.5 m long.
- Robotic arm has 5 actuators.
- Arm and payload has a mass of ~ 100 kg.
 - Arm and payload is 10% of the mass of the entire rover.
 - MSL arm is more than twice as long as the MER IDD and has a payload that is more than 15x more massive.
 - MSL arm cabling alone is more massive than entire MER IDD.
- Arm Operations:
 - Contact Science
 - Rover Self-Inspection
 - Sample Acquisition
 - Sample Processing
 - Sample Delivery
 - Cached Sample Manipulation

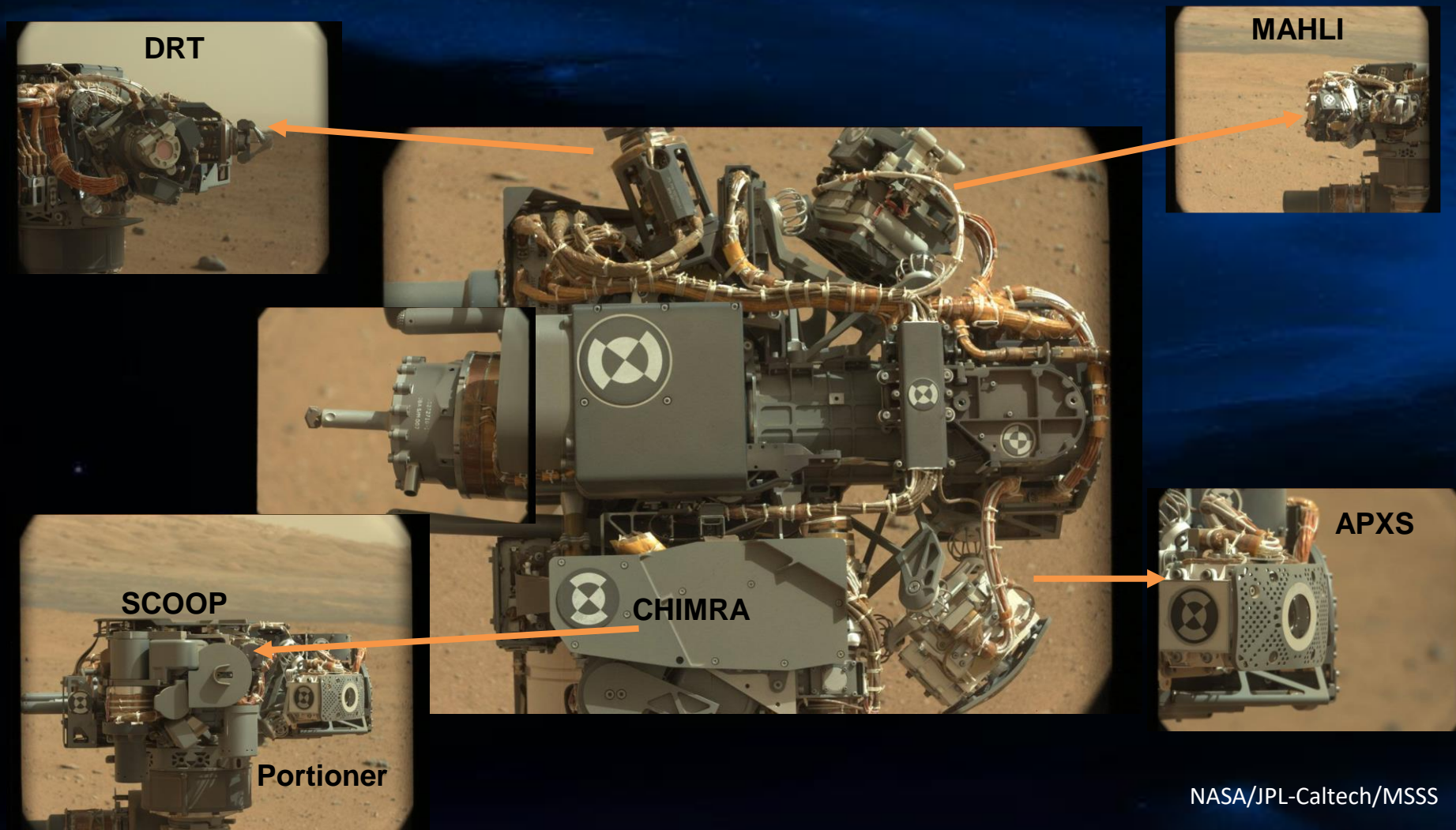


Robot Arm

- The arm and turret together have a mass of approximately 100kg and a reach of over 2 m. This accounts for nearly 10% of the entire mass of the rover. The cabling alone weighs more than either the entire Phoenix robotic arm or MER arm (IDD).
- The MSL robotic arm (RA) is the most complex yet most capable manipulator ever sent to another planetary surface. The robotic arm is a 5 degree-of-freedom manipulator supporting a 30-kg payload mounted at the end of the arm.
- Essentially the primary function of the RA is to position the turret-mounted instruments and tools with respect to Mars surface or rover-mounted targets.



Turret

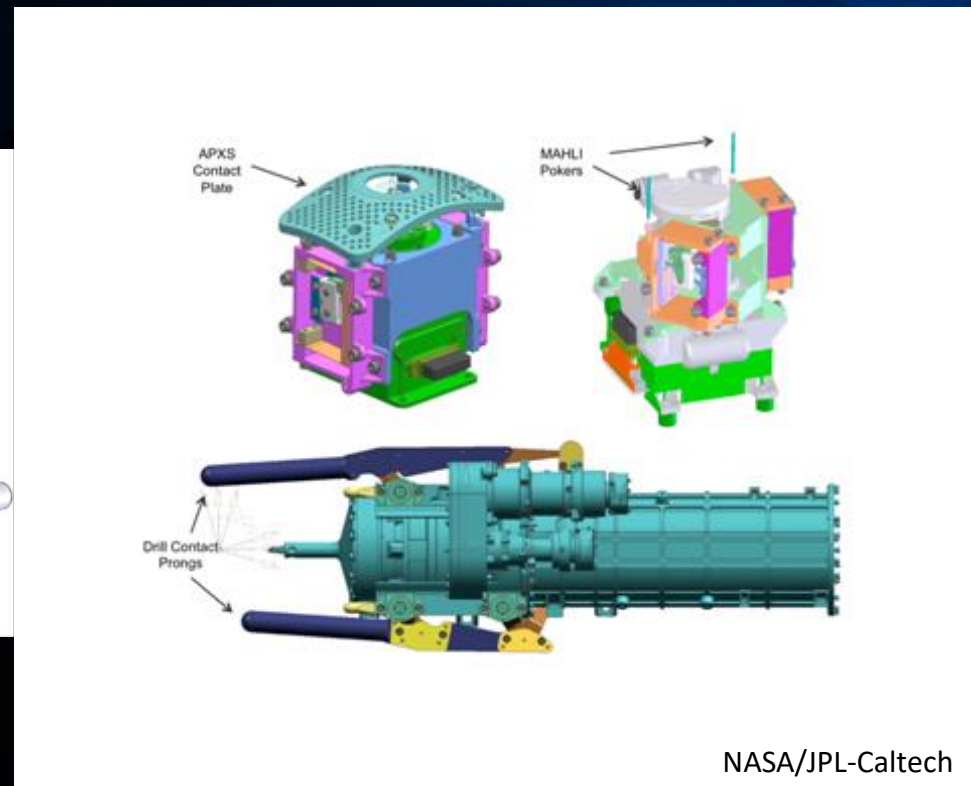
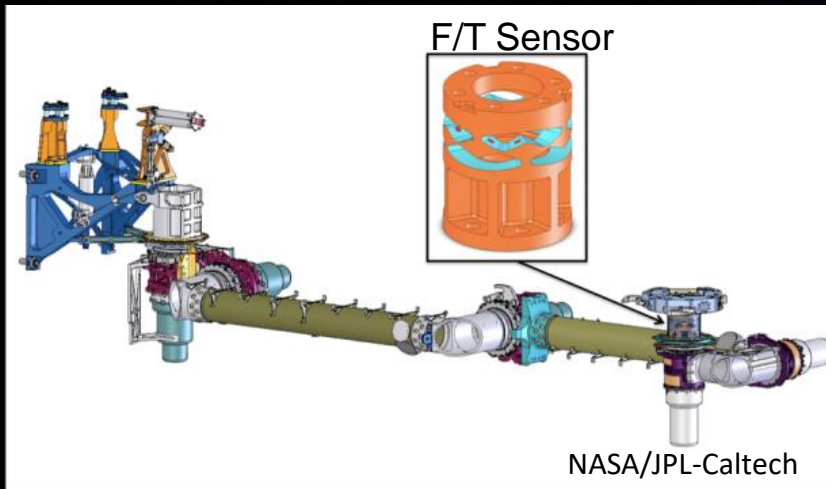


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Arm Sensors

- The arm has a Force/Torque Sensor mounted in the turret.



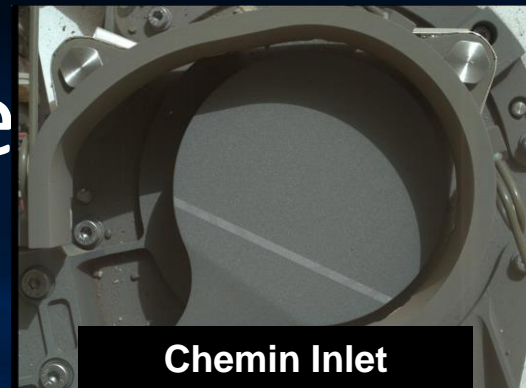


Rover Workspace



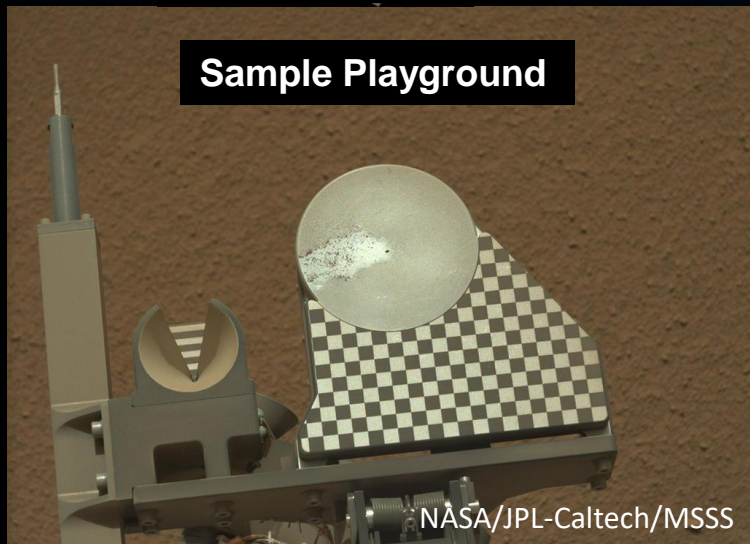
OCM

NASA/JPL-Caltech/MSSS



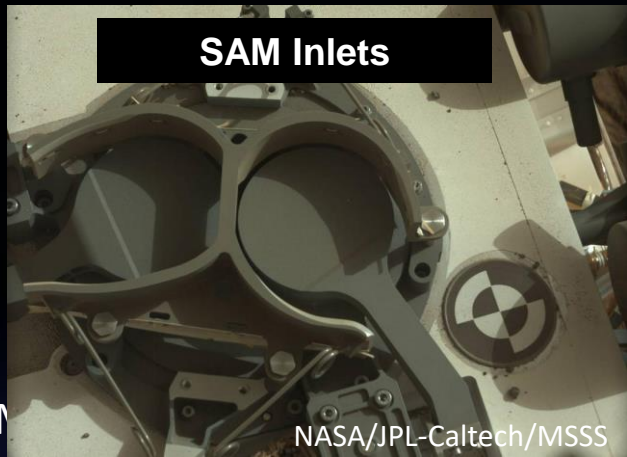
Chemin Inlet

NASA/JPL-Caltech/MSSS



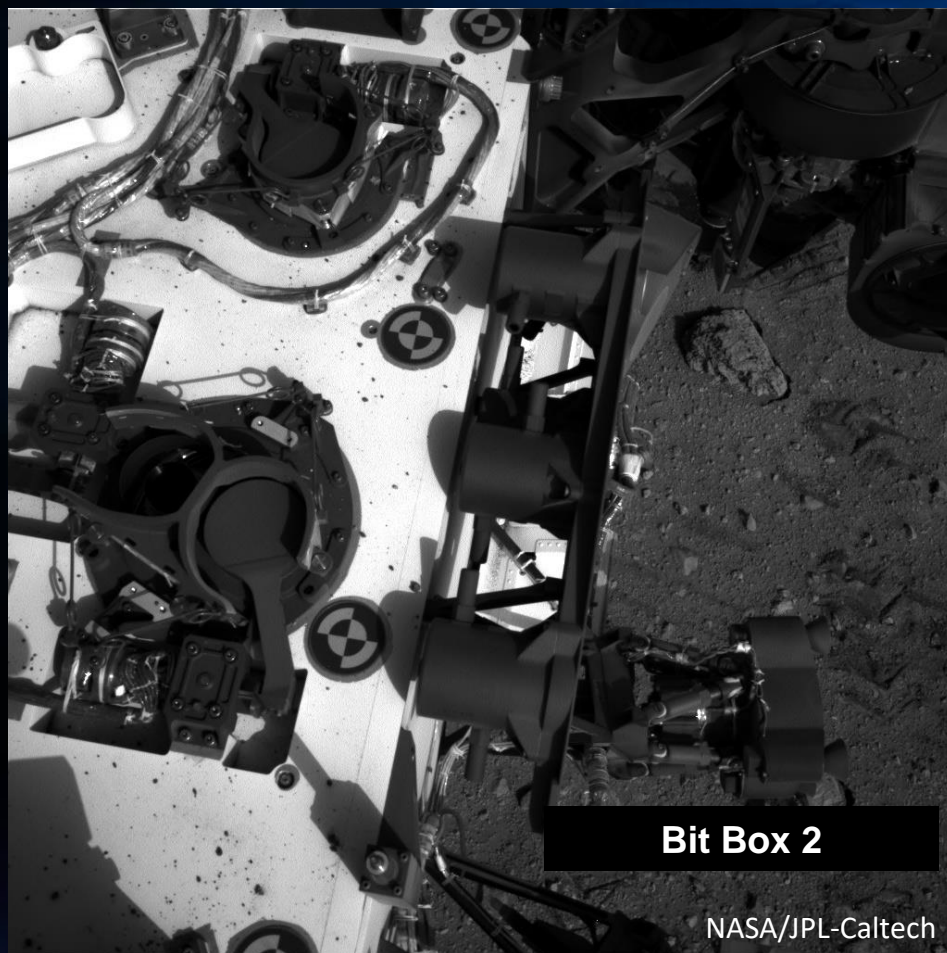
Sample Playground

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SAM Inlets

NASA/JPL-Caltech/MSSS



Bit Box 2

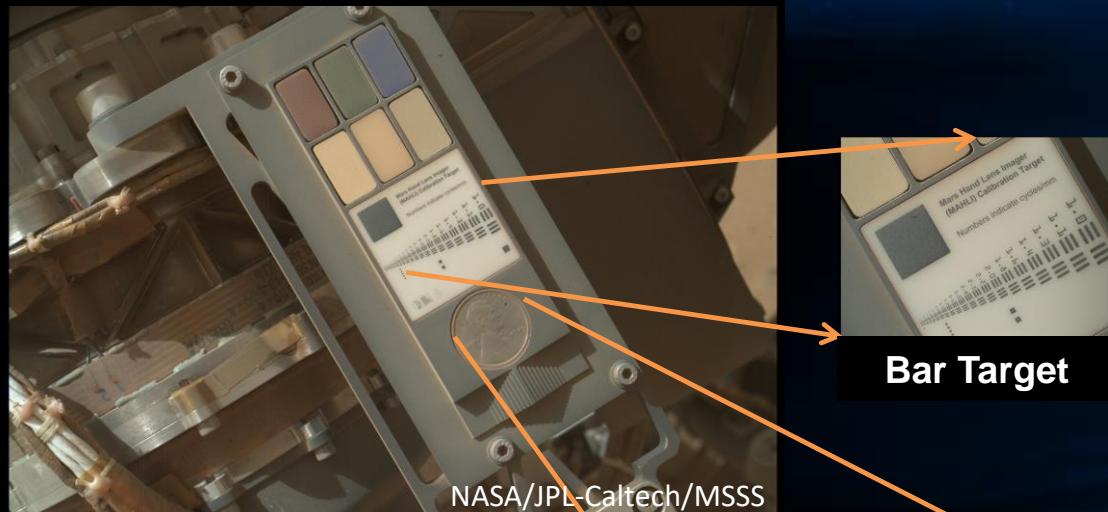
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MAHLI and APXS Cal Targets

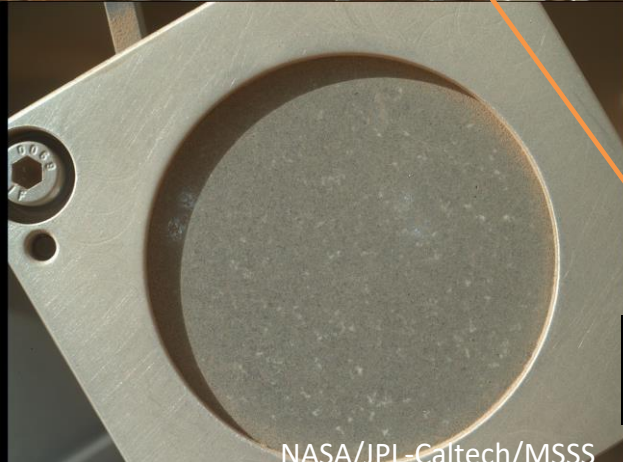
- MAHLI and APXS Cal targets are mounted on arm shoulder and rotate with azimuth.

FM MAHLI Cal Target as imaged by MAHLI



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Bar Target

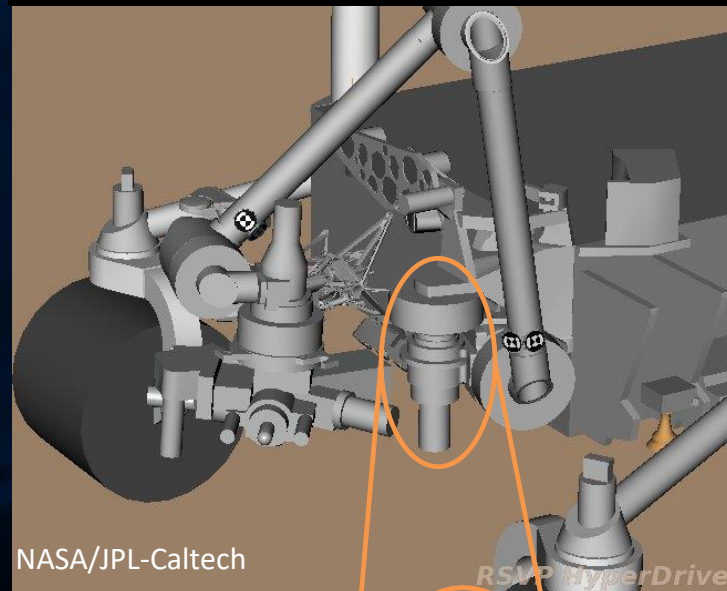


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**Hi Res image of penny
16 microns/pixel**

RA in MAHLI cal target pose



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RSVP HyperDrive



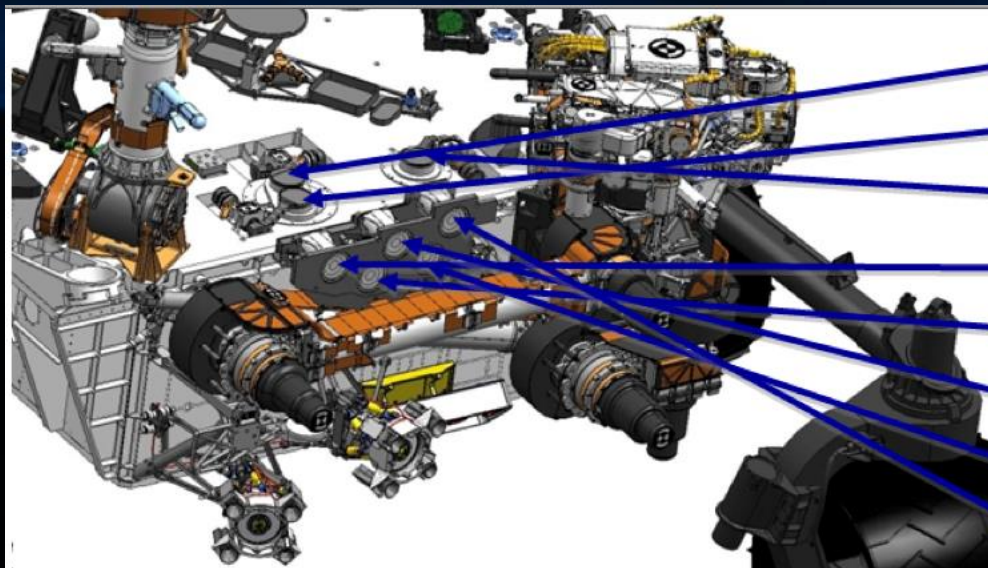
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EM MAHLI cal target

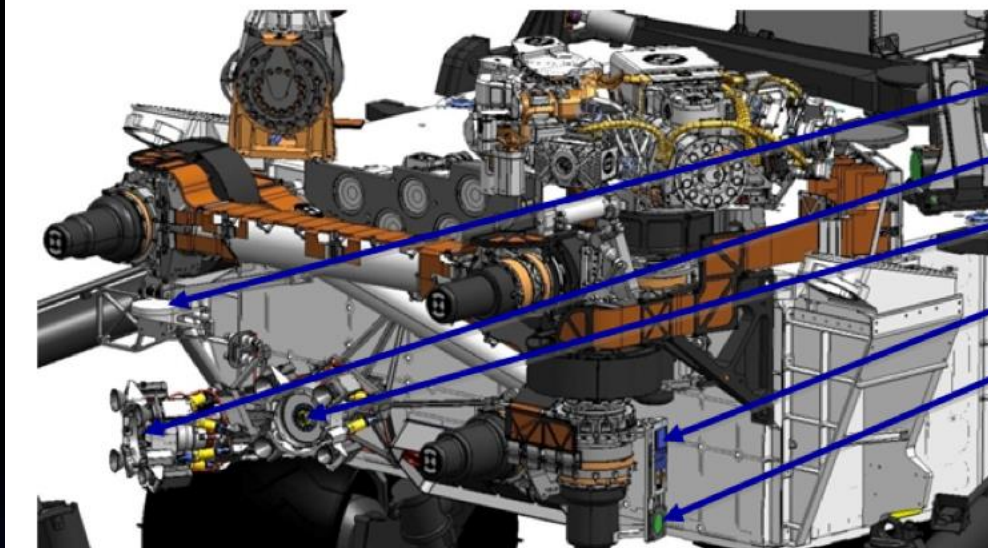
Basalt APXS Cal Target as imaged by MAHLI



Robot Arm Teach Points



SAM Inlet 1
SAM Inlet 2
CheMin Inlet
OCM 1
OCM 2
OCM 3
OCM 4
OCM 5

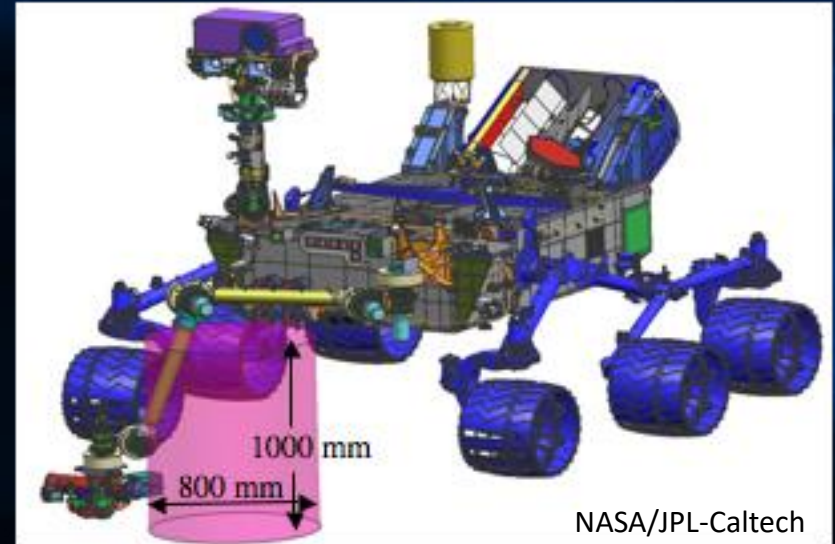
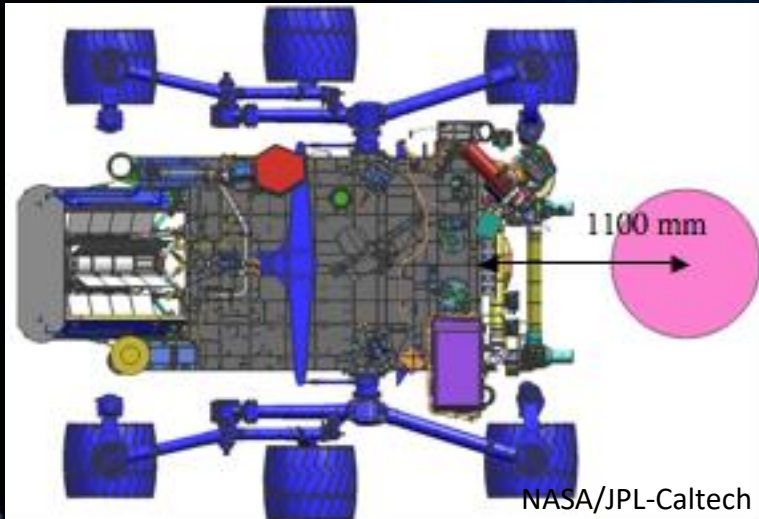


Observation Tray
Bit Box 1
Bit Box 2
MAHLI Cal Target
APXS Cal Target

NASA/JPL-Caltech



Robotic Arm “Magic Cylinder” Workspace



The cylinder extends 200mm below the front wheels

The magic cylinder is a construct used to specify arm requirements and is not the entirety of the arm science workspace. The Robotic Arm moves tools and instruments to the workspace in front of the Rover. Arm can apply minimum of 300 N force on targets in most of the workspace.

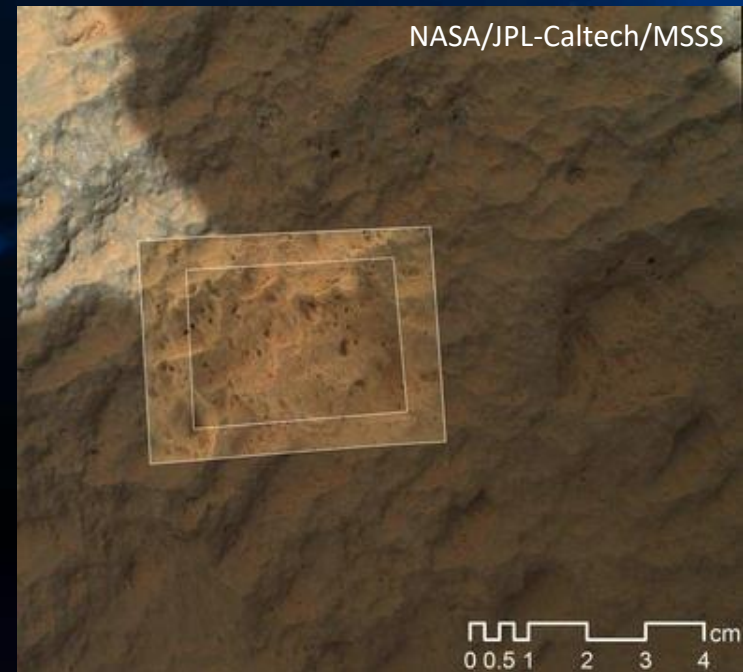


Planning Multiple Arm Activities: Sol 612



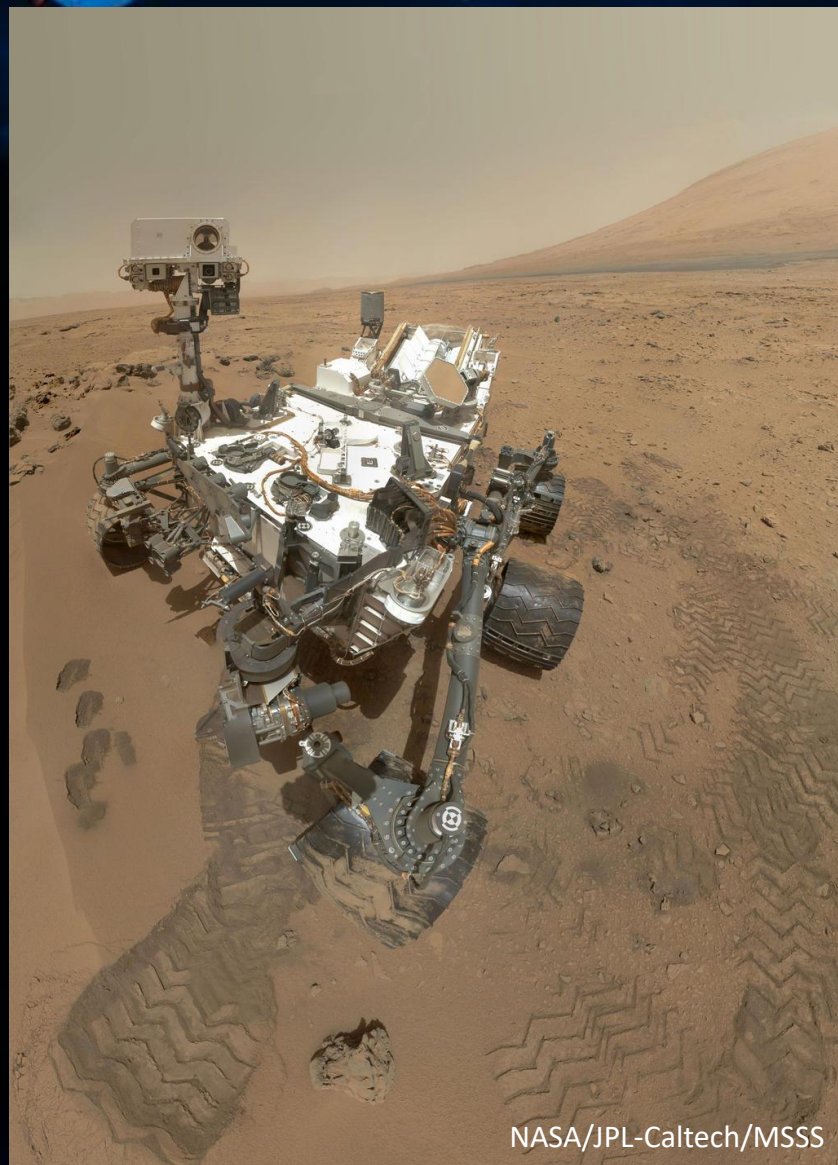


Contact Science

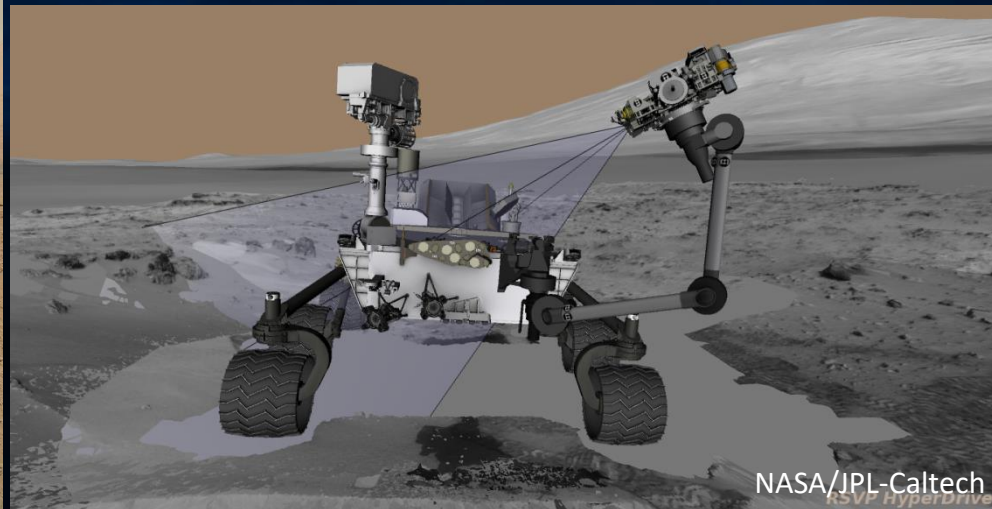




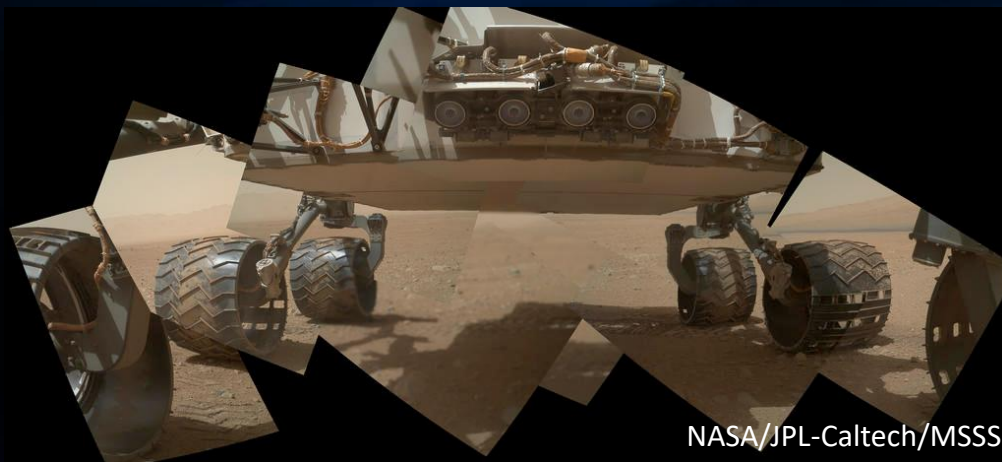
Rover Self-Inspection



NASA/JPL-Caltech/MSSS



NASA/JPL-Caltech



NASA/JPL-Caltech/MSSS

CMU 2016

“Self” Portrait

Belly Pan



Rover Self-Inspection

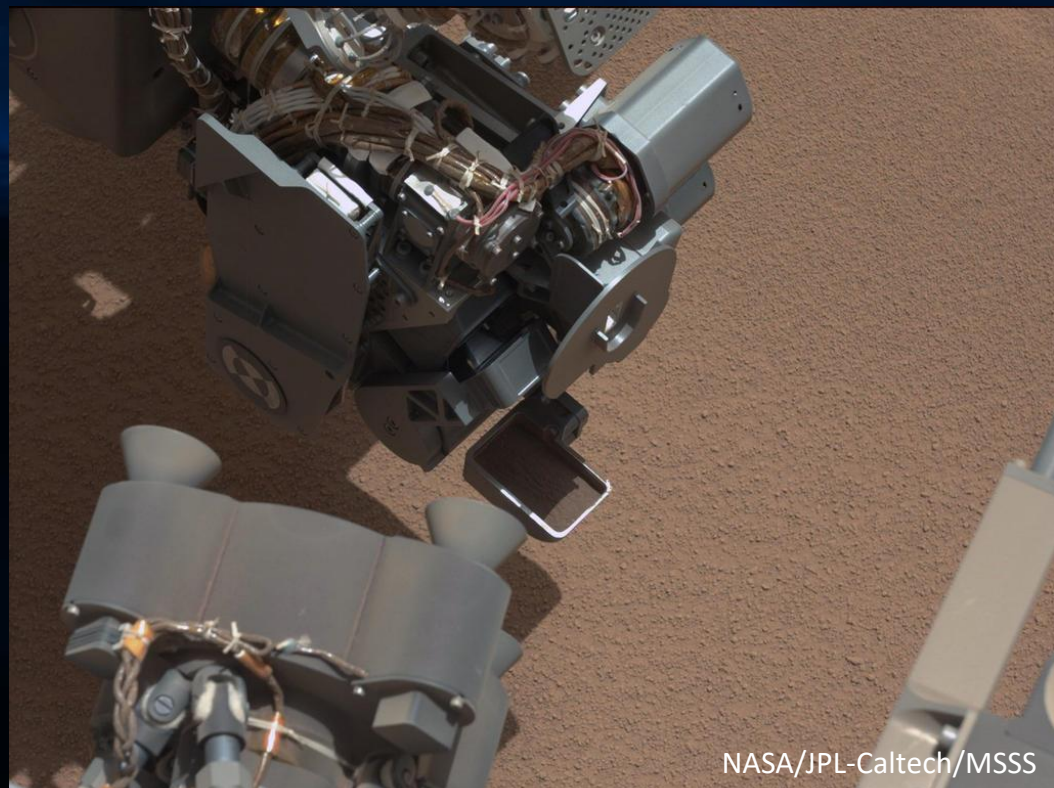
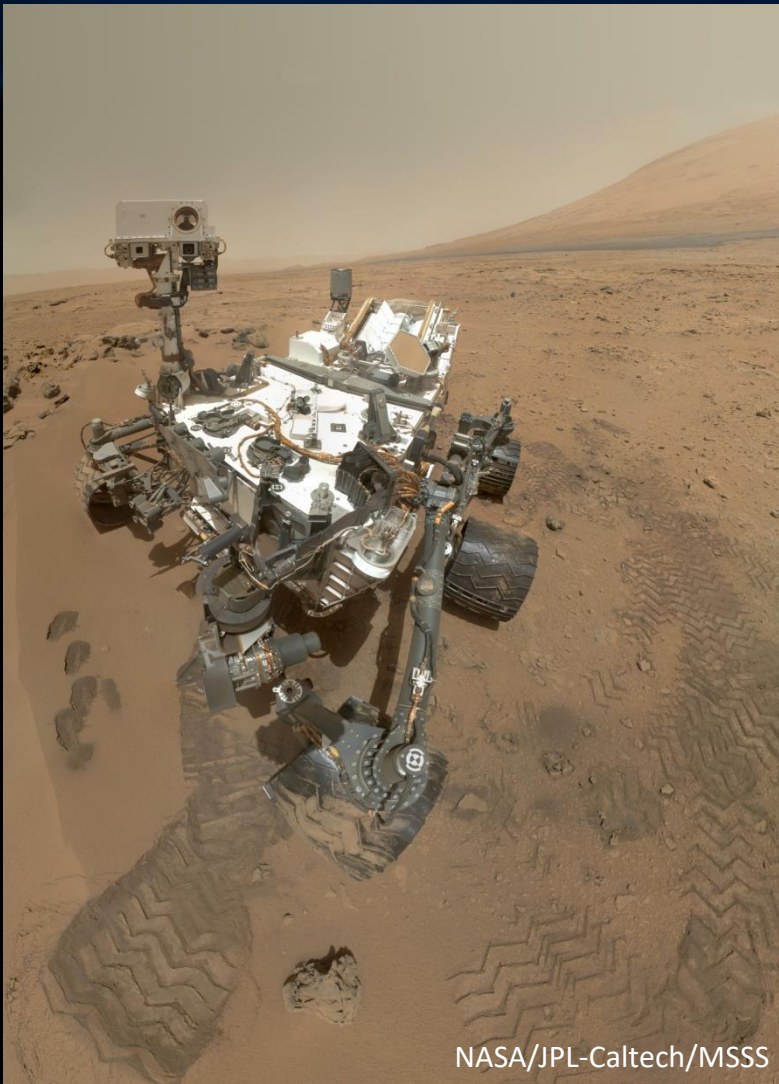
Animation of **Curiosity Rover's Arm Movements** for Taking a **Self-Portrait**



NASA/JPL-Caltech

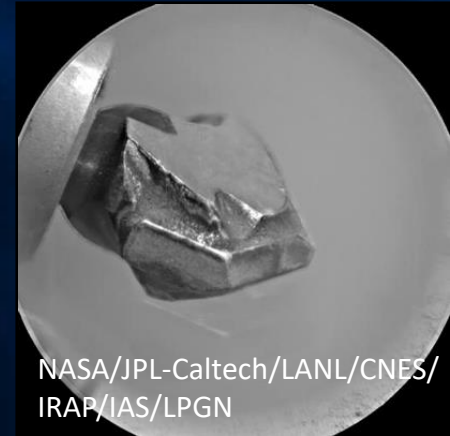


Scooping





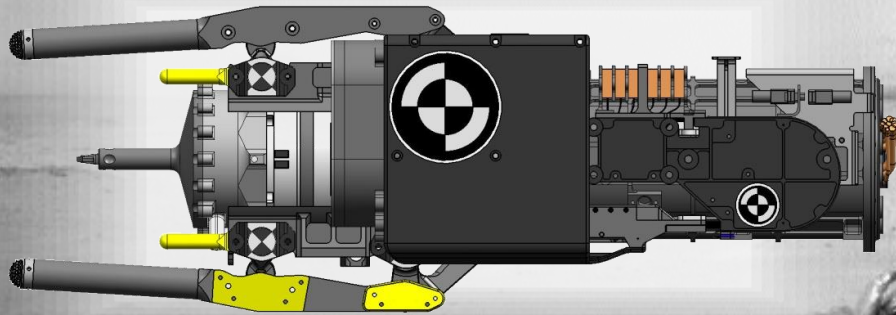
Drilling



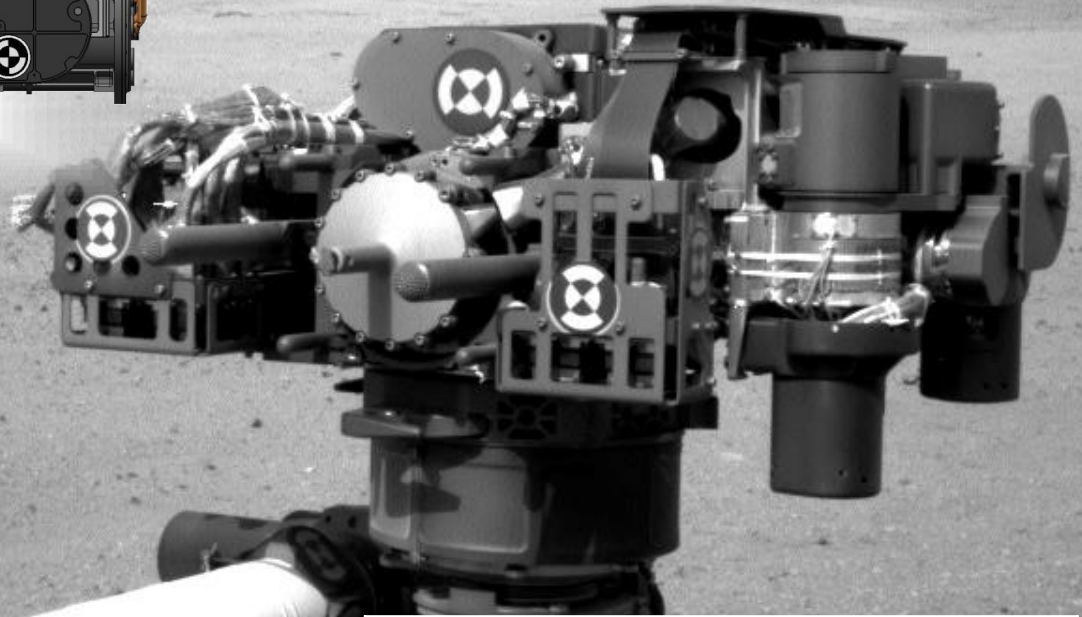
Target John Klein

CMU 2016

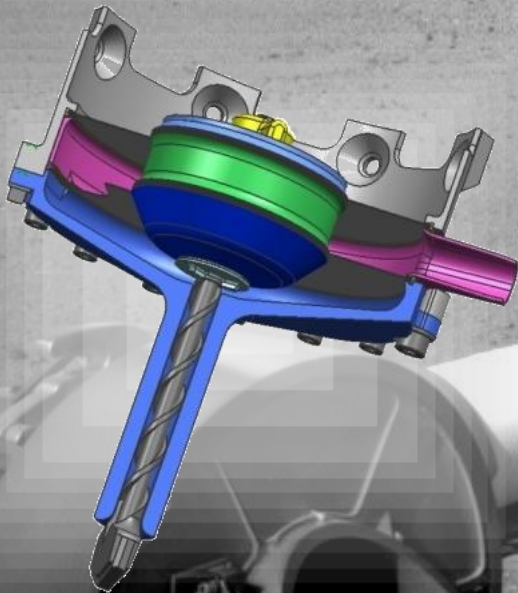
Top View of Curiosity's Drill



Curiosity's Turret



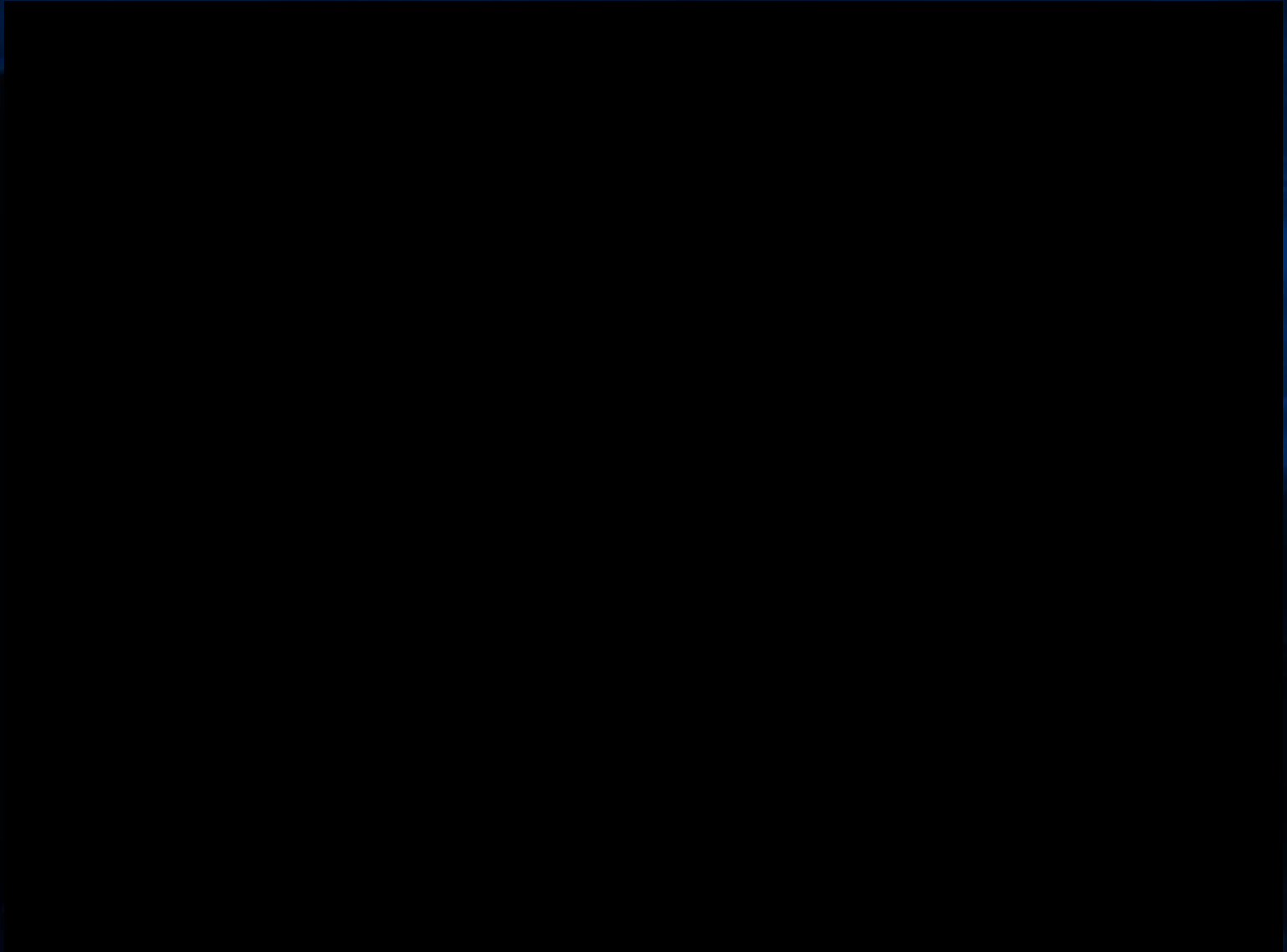
Section View of Curiosity's Drill Bit



Drill Specifications	
Spindle Rotation Rate	107 RPM
Spindle max torque	4.8 N-m
Percussion impact energy	0.05 to 0.8 J
Percussion rate	1800 BPM
Bit retraction force	4600 N
Translation stroke	65 mm beyond contact plane
Contact Sensing	Trigger force < 40 N
Bit Release capability	Full rover Mars weight on 20° slope
Structural capability	Full rover Mars weight on 20° slope

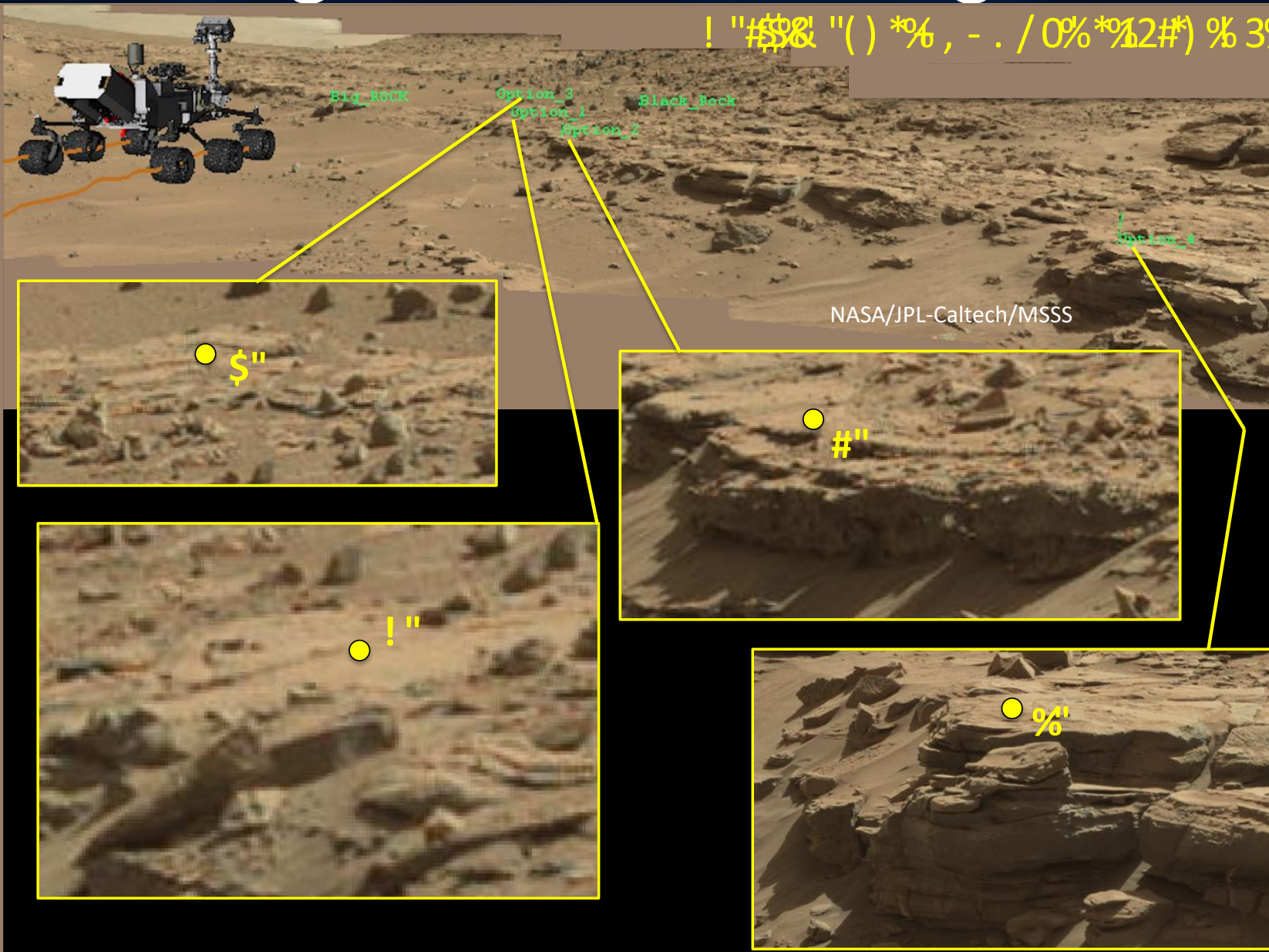


Testbed Drill in Action





Evaluating Possible Drill Targets





Sol 615 Mini-drill Results



NASA/JPL-Caltech/MSSS



NASA/JPL-
Caltech/LANL/CNES/IRAP/IAS/LPGN



NASA/JPL-Caltech/MSSS

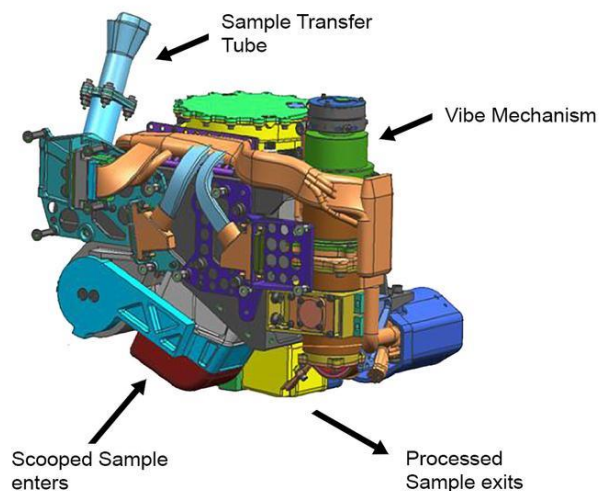


**Curiosity's 1.6-cm drill bit, drill and test holes,
and scoop full of acquired sample**

EMC 2016

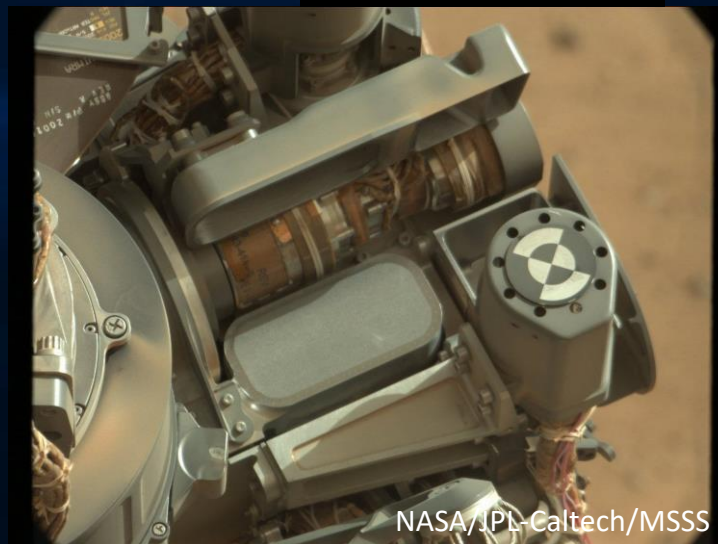


Sample Processing



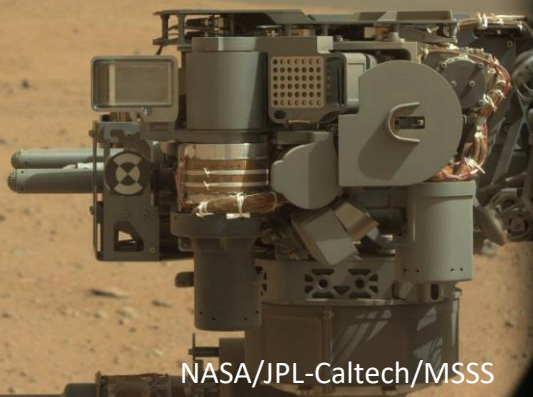
NASA/JPL-Caltech

150 micron sieve



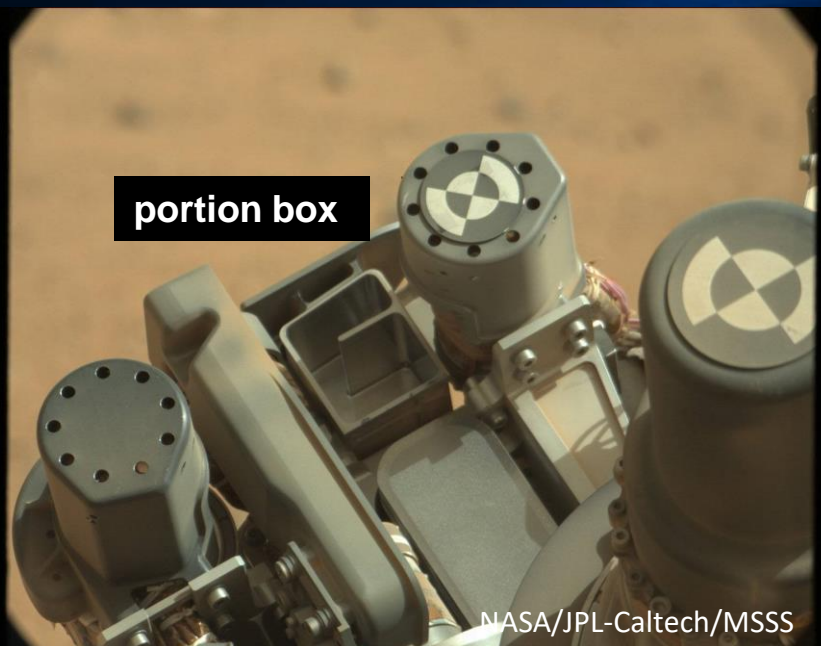
NASA/JPL-Caltech/MSSS

1mm sieve



NASA/JPL-Caltech/MSSS

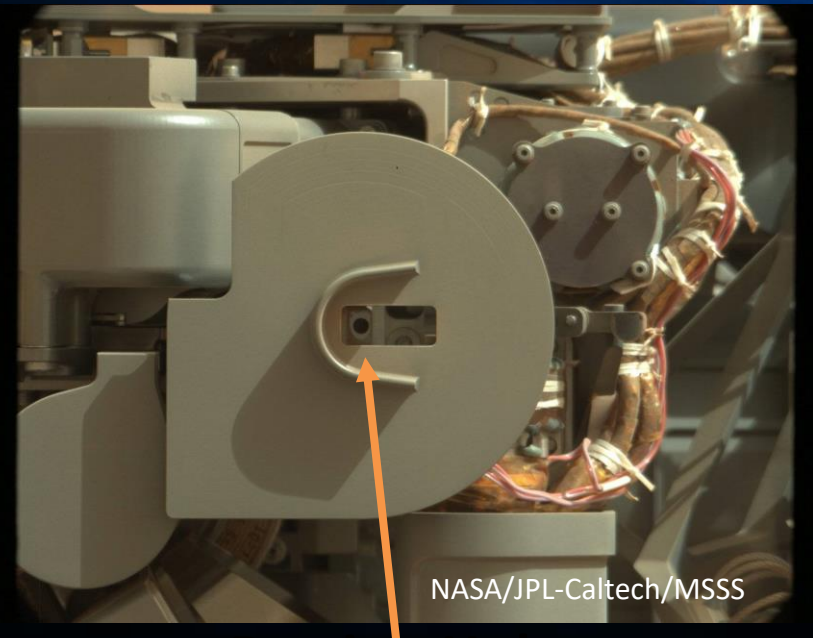
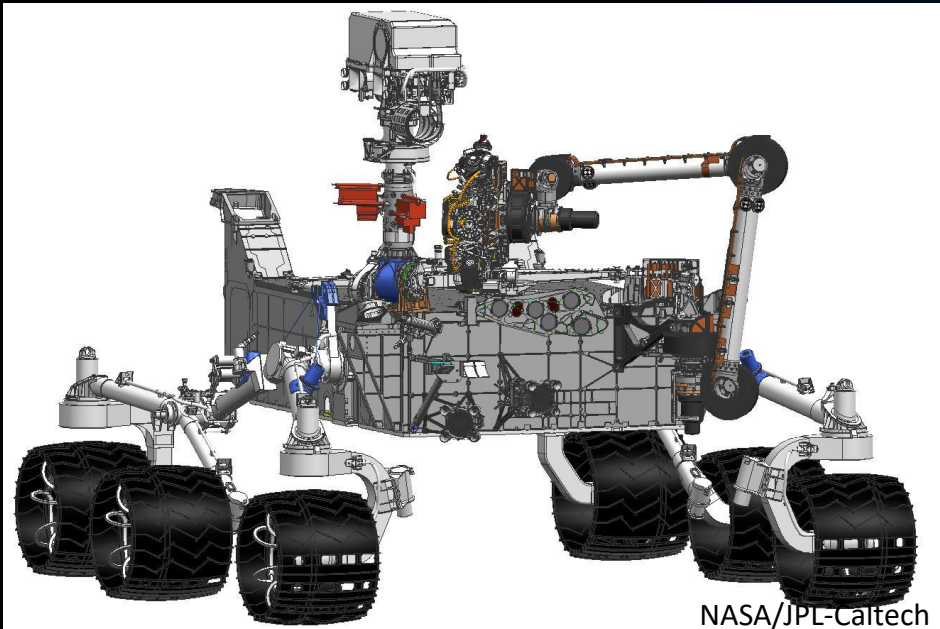
portion box



NASA/JPL-Caltech/MSSS



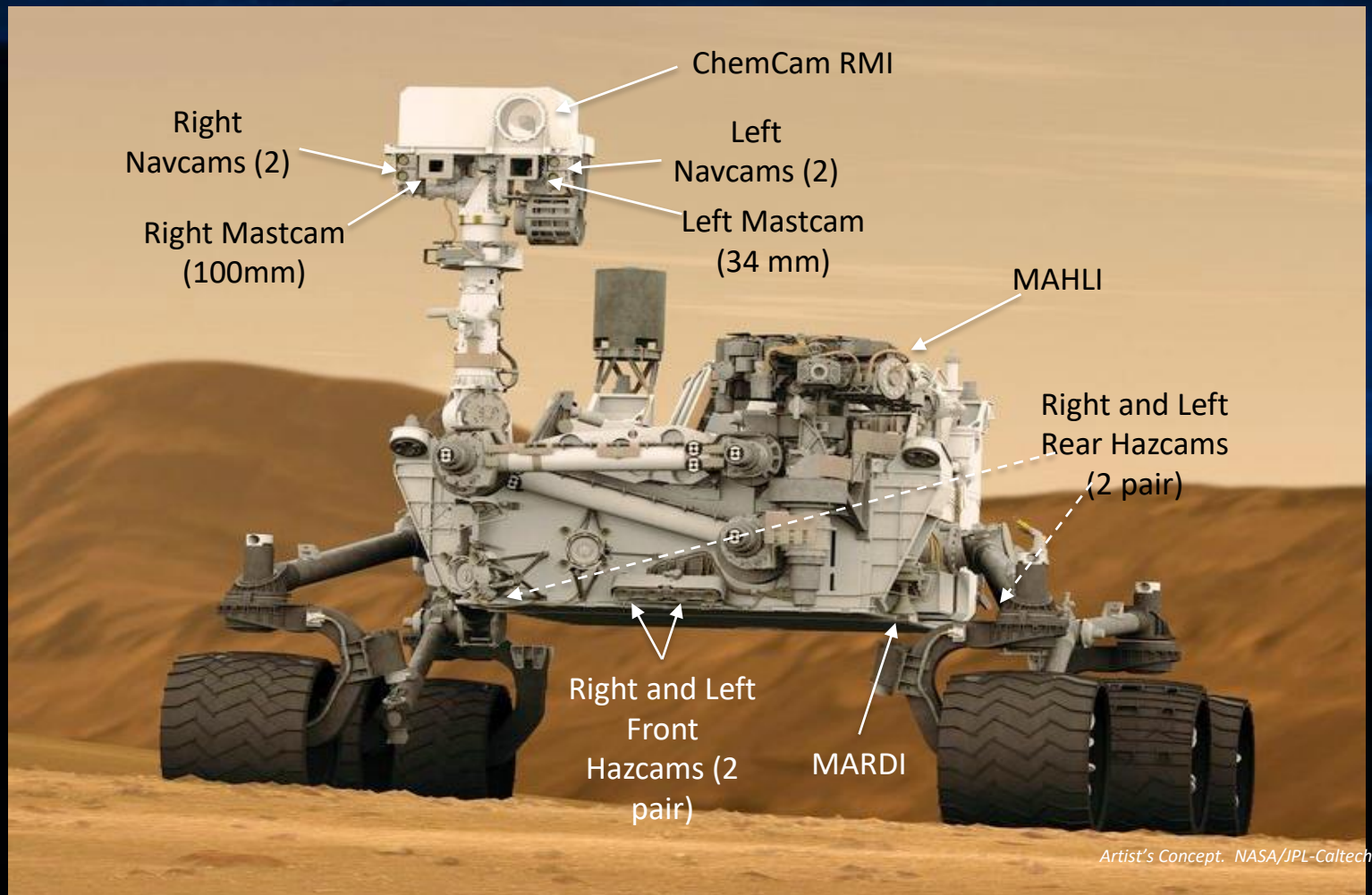
Sample Delivery



Portion Hole
3 mm diameter



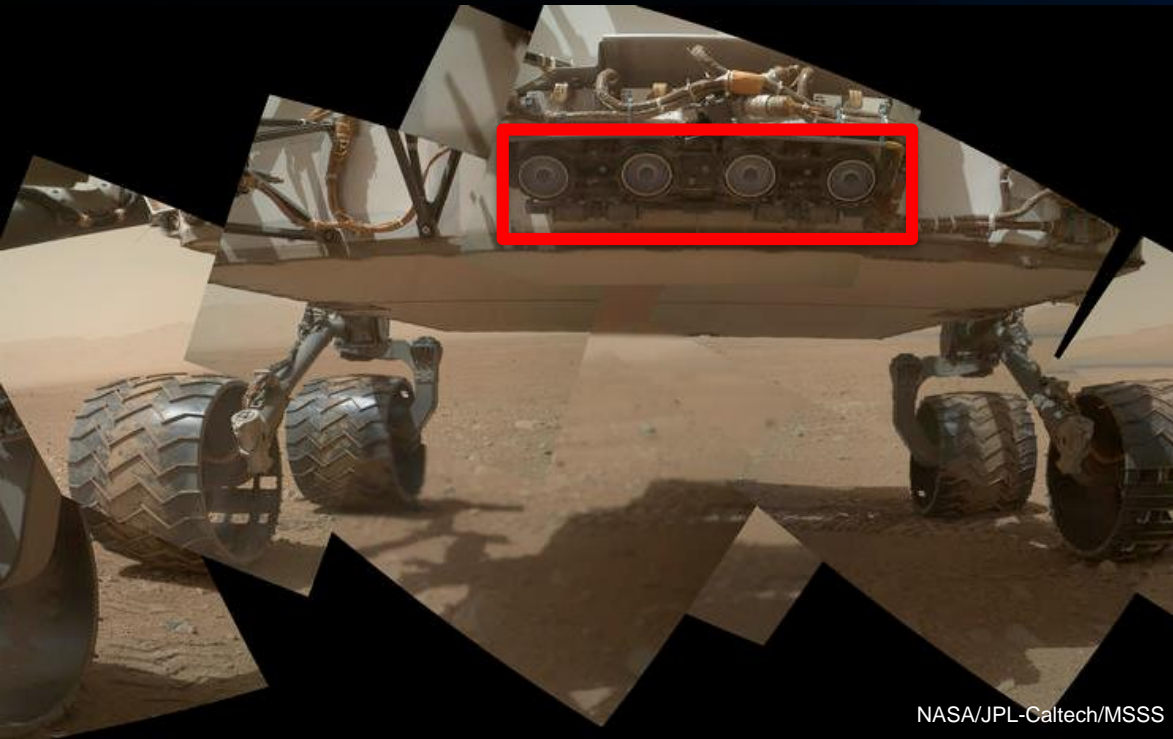
Curiosity has 17 cameras



However, only the Hazcams and Navcams are tied into the auto-nav software.



The hazard avoidance cameras give a 120° wide angle view of the area near the rover. Front cameras have 16cm baseline, rear cameras have 10cm baseline.



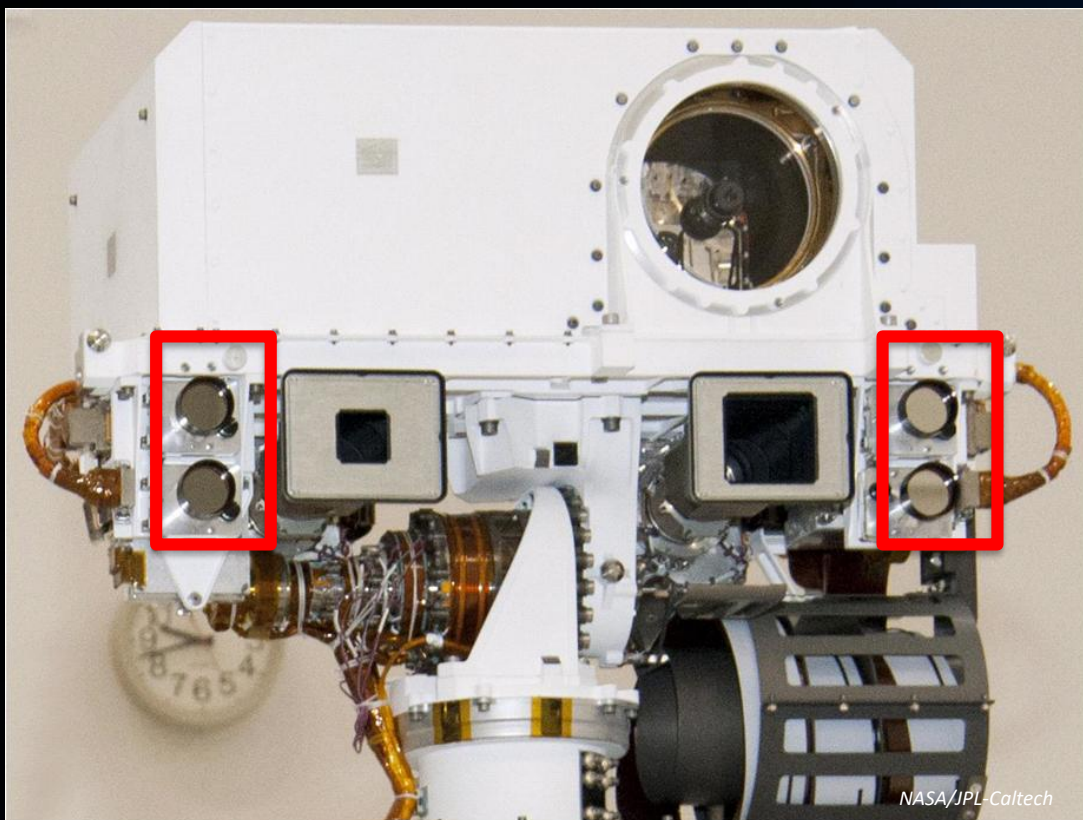
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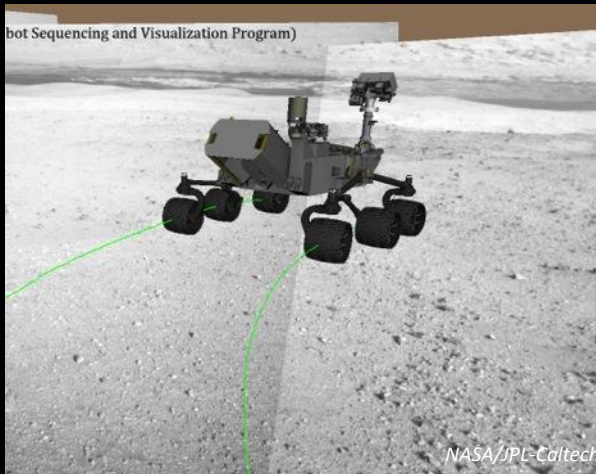


The 45° navigation cameras are almost 7 feet off the ground with 42cm baseline, providing good views over nearby obstacles or hills and into ditches.





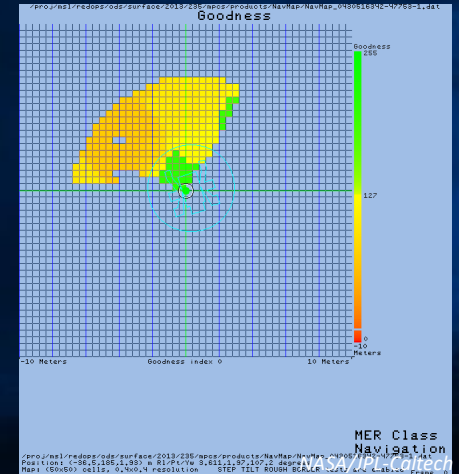
Human Rover Drivers Decide How Much Autonomy is Desired Based on Terrain and Available Resources



Directed driving



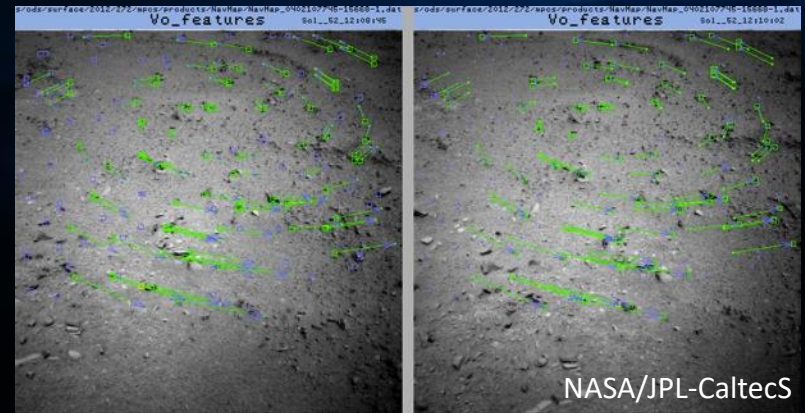
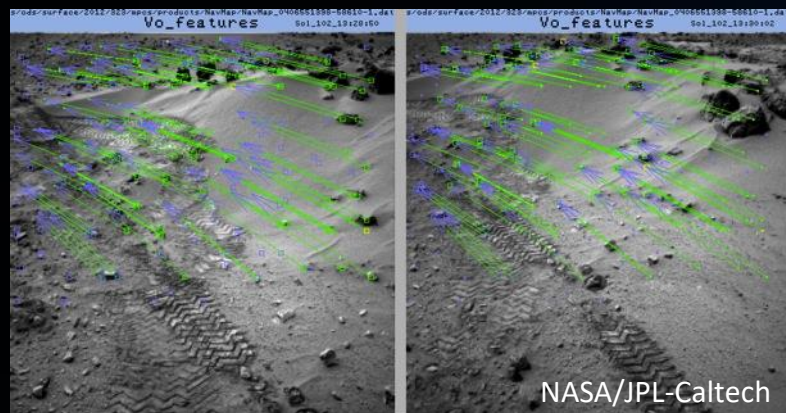
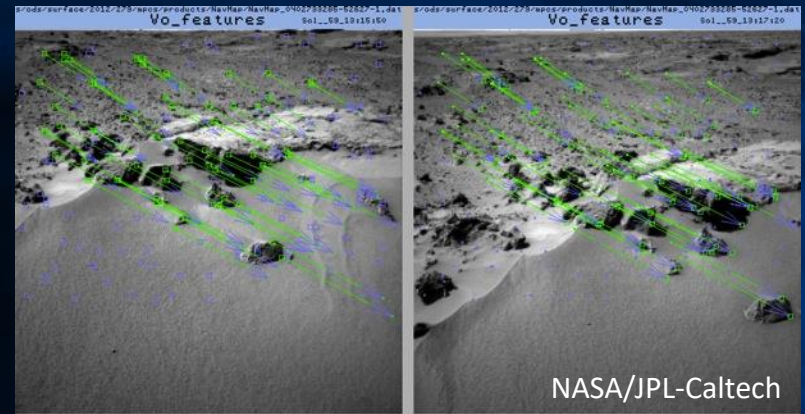
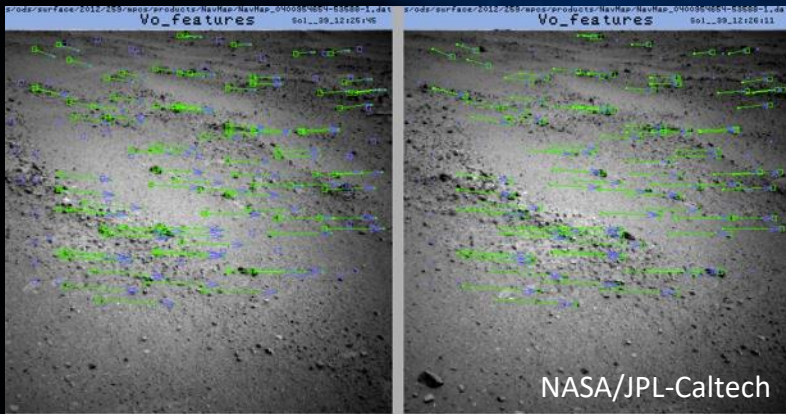
Visual odometry, or
Slip Check + “Auto”



Auto-navigation;
Geometric Hazard
Detection and
Avoidance



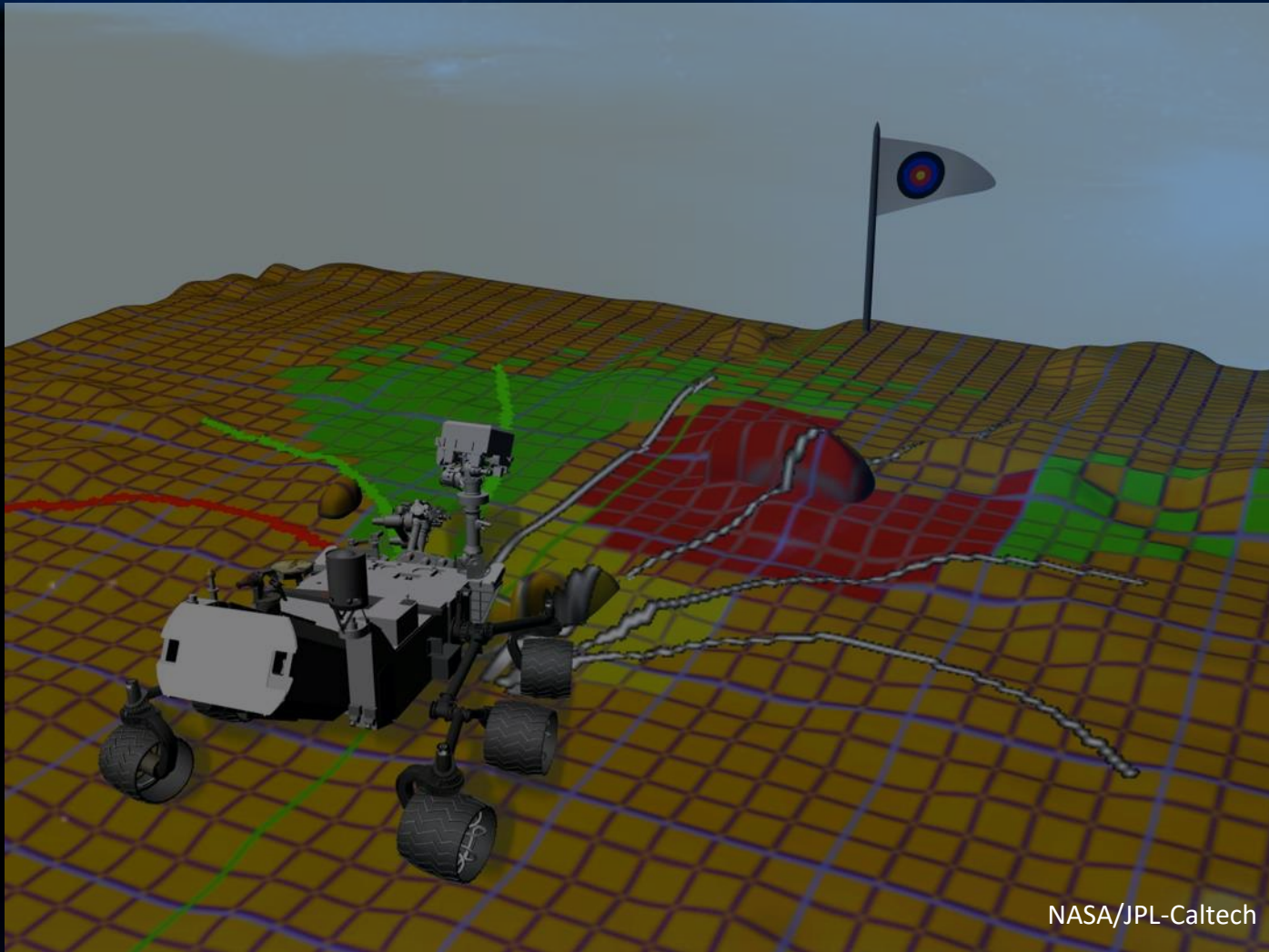
Using visual odometry, the rover constantly compares pairs of images of nearby terrain to calculate its position.



Unlike terrestrial robots, Curiosity drives as far as possible between VO images



Human drivers *and* Curiosity depend on 3D image analysis to find the safest path.



NASA/JPL-Caltech



During nominal auto-nav, the rover stops every 0.5-1.5 meters, takes 4 sets of images, evaluates hazards, and then chooses where to drive.

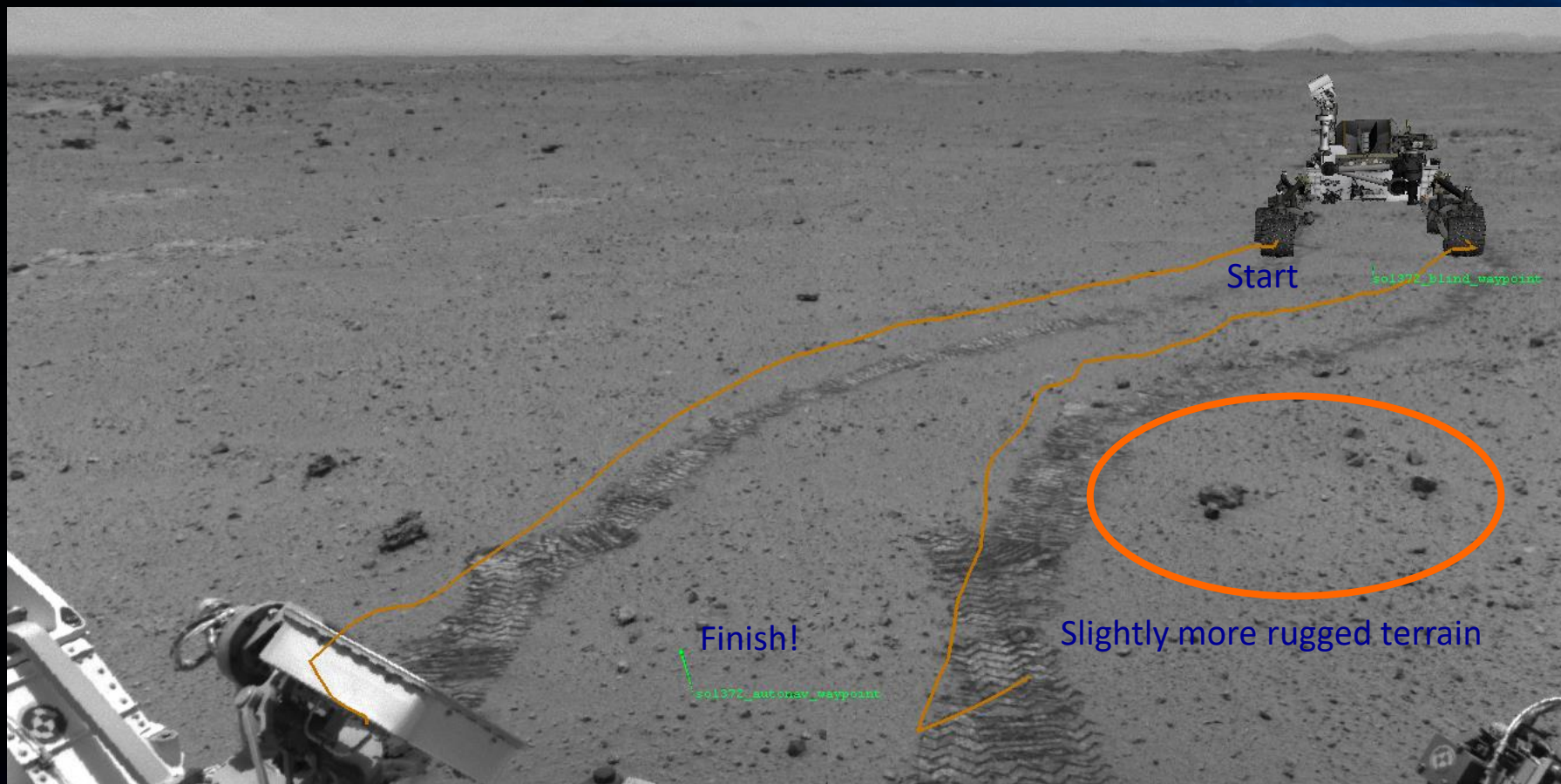


Artist's Concept. NASA/JPL-Caltech

Auto-nav extends directed drives into previously unseen terrain

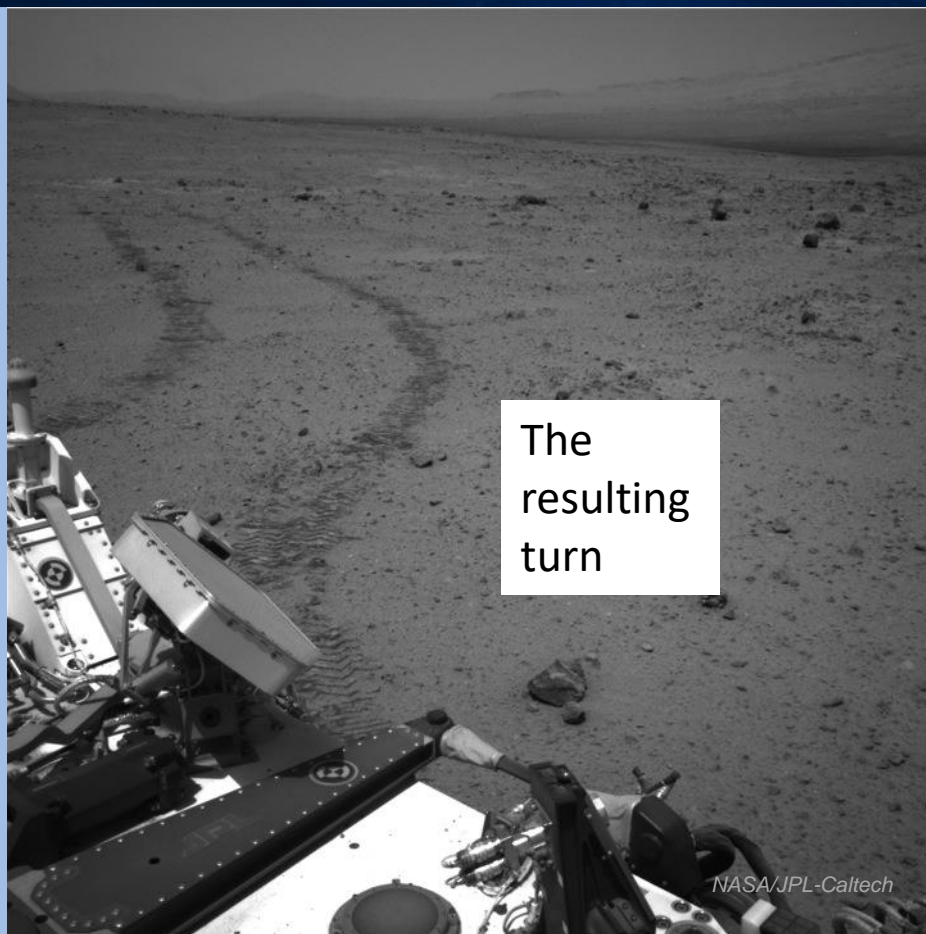
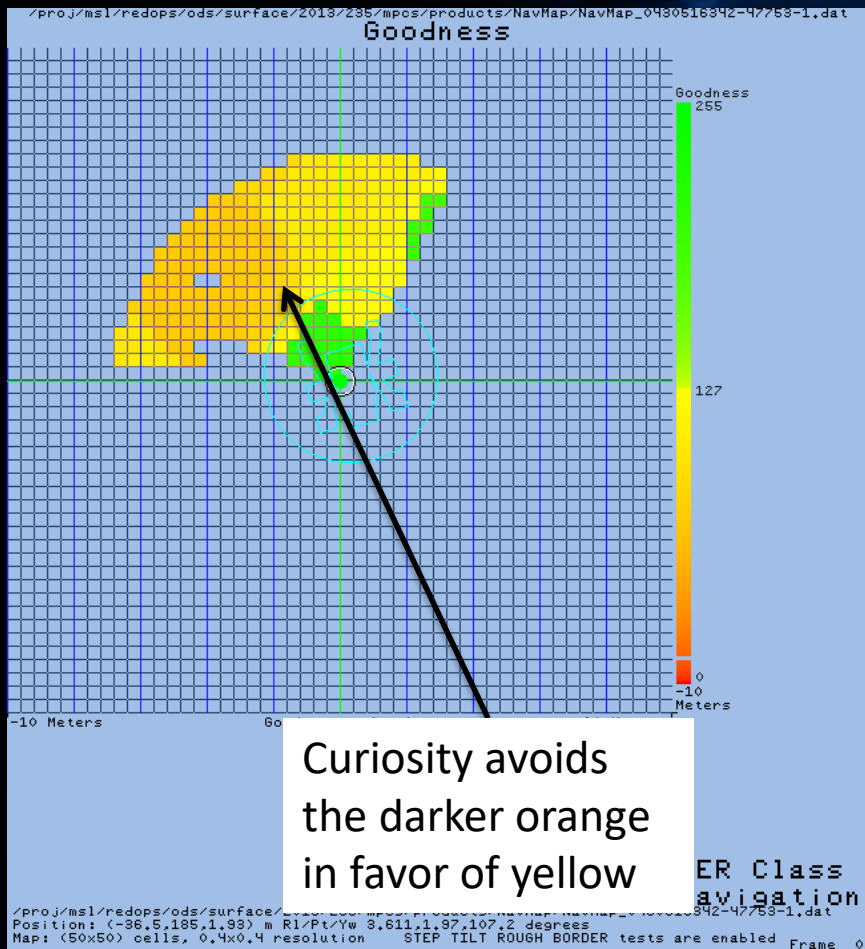


Wheel tracks after the first auto-nav drive on sol 372 show that Curiosity chose to drive around a little mound of loose rock.



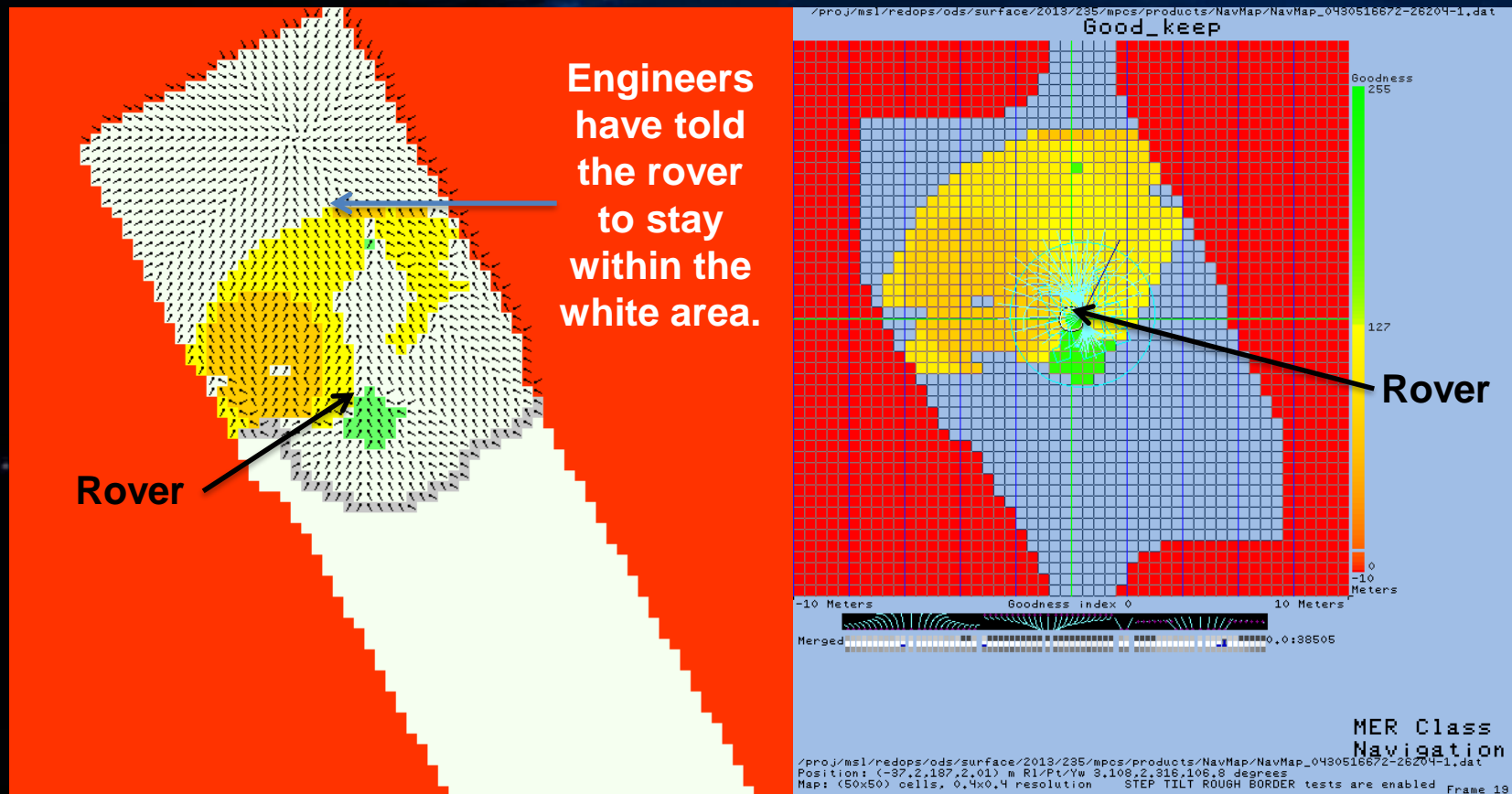


Curiosity's map and tracks show this decision to turn was based on her evaluation of the terrain.





The rover reduces a stereo point cloud into a configuration space, labeling unsafe areas red and safe areas green.

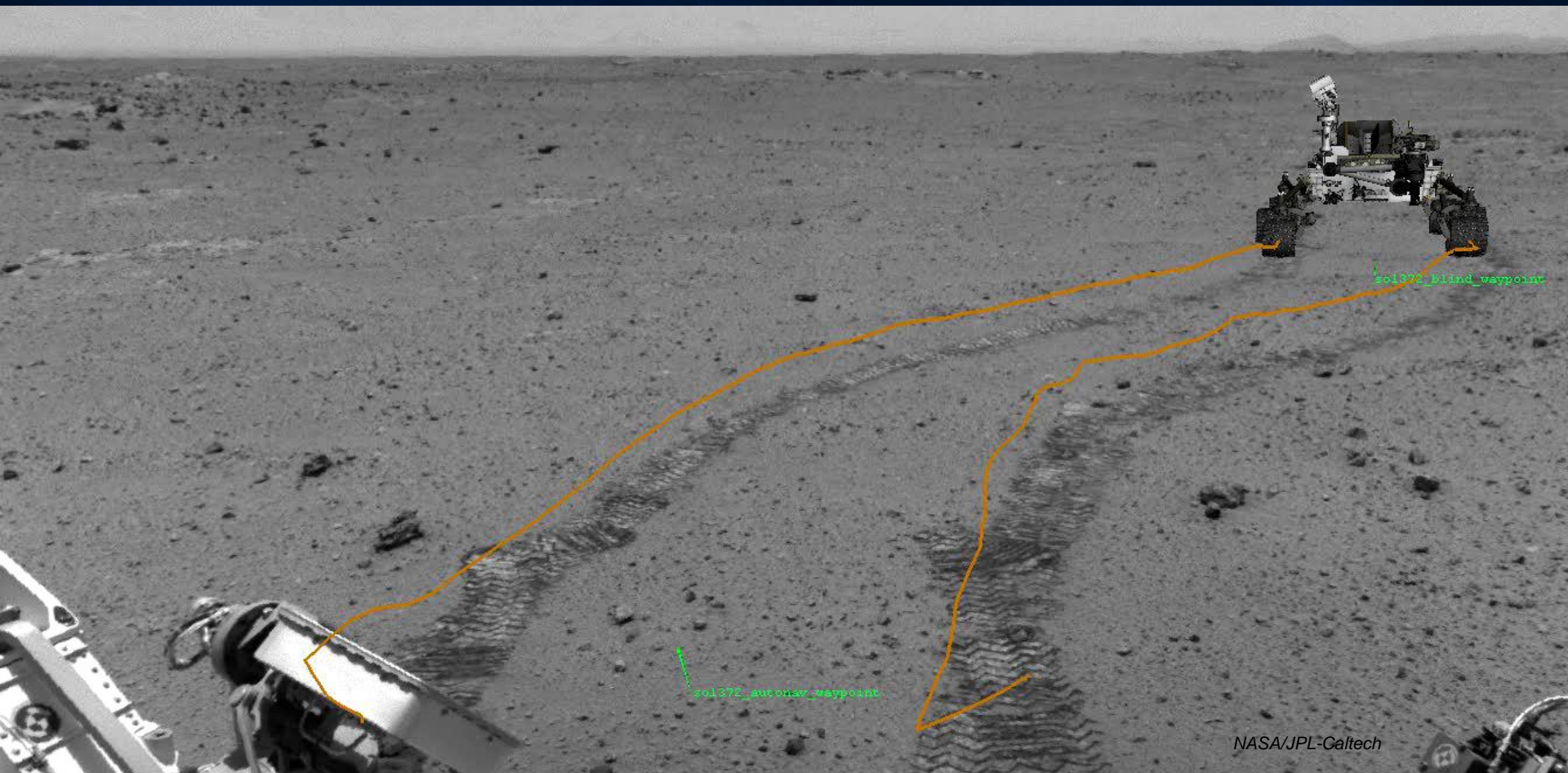


NASA/JPL-Caltech

Yellow means drive carefully, just like on Earth.



Animation of Curiosity's actual Sol 372 drive over a picture of her tracks



NASA/JPL-Caltech

Finish!



WDC? Challenges!

Artist's Concept. NASA/JPL-Caltech



Sol 122: VO vs IMU

- By convention, any VO updates that measure more attitude change than the IMU does will be rejected; we tend to trust the IMU, especially over short distances
- On Sols 122-124, Curiosity drove using Visual Odometry (VO), but several VO updates were rejected!
- Turned out that VO was right! A parameter caused the IMU gyro-based attitude estimator to reject changes under high accelerations
- No more issues since updating that parameter
- *VO updates have failed to converge just 13 times out of 3855 attempts as of sol 650, and only twice for actual lack of texture; **99.66% success rate!***



Sol 200: Flash Anomaly

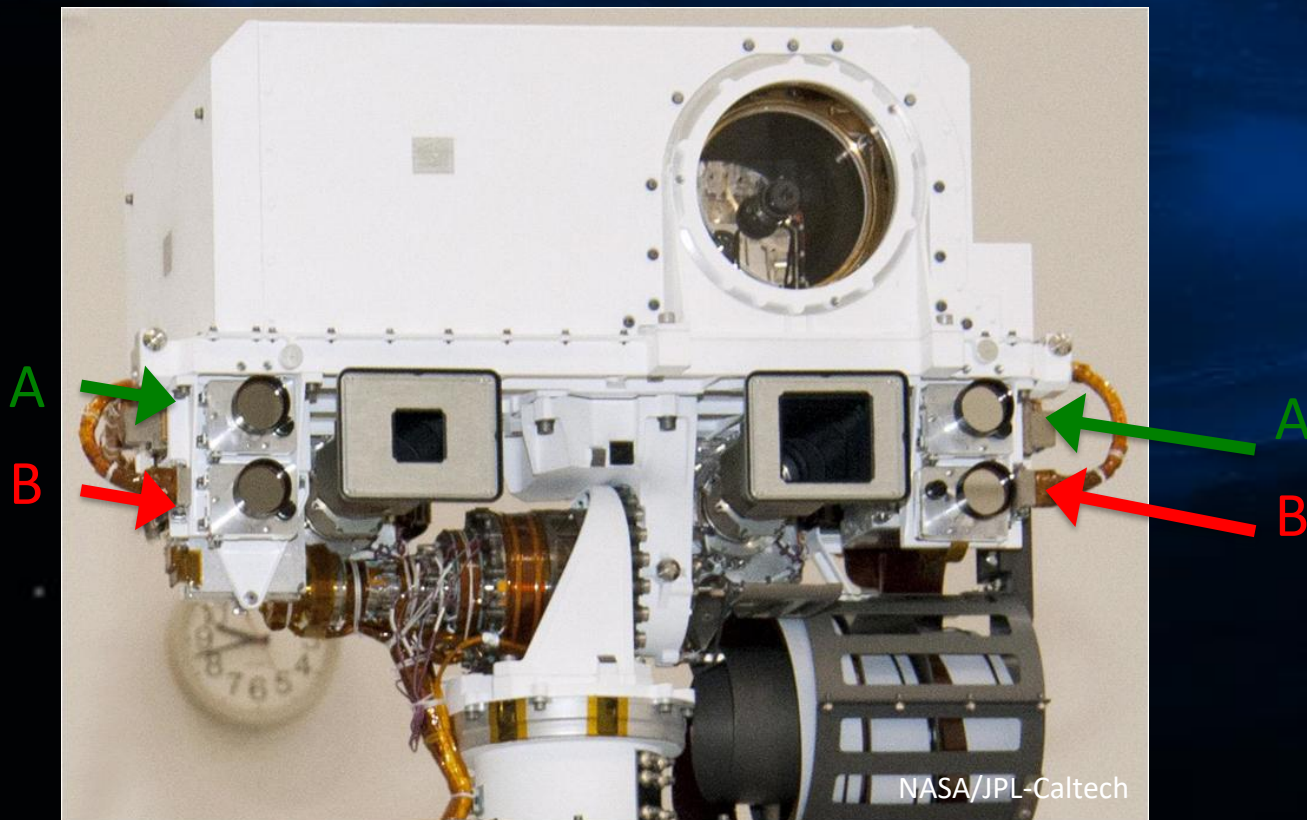
- On Sol 200, Curiosity's primary CPU (on Rover Compute Element A, or RCE-A) detected a problem in the flash memory and rebooted into the backup RCE-B CPU.
- The team determined the safest strategy would be to mark half the available RCE-A flash as unusable, and continue the mission on the backup RCE-B CPU.
- We've been using the backup RCE-B ever since

Artist's Concept. NASA/JPL-Caltech



Sol 201: Backup Navcams

When the B-side computer (RCE-B) became prime, Curiosity also switched to backup cameras

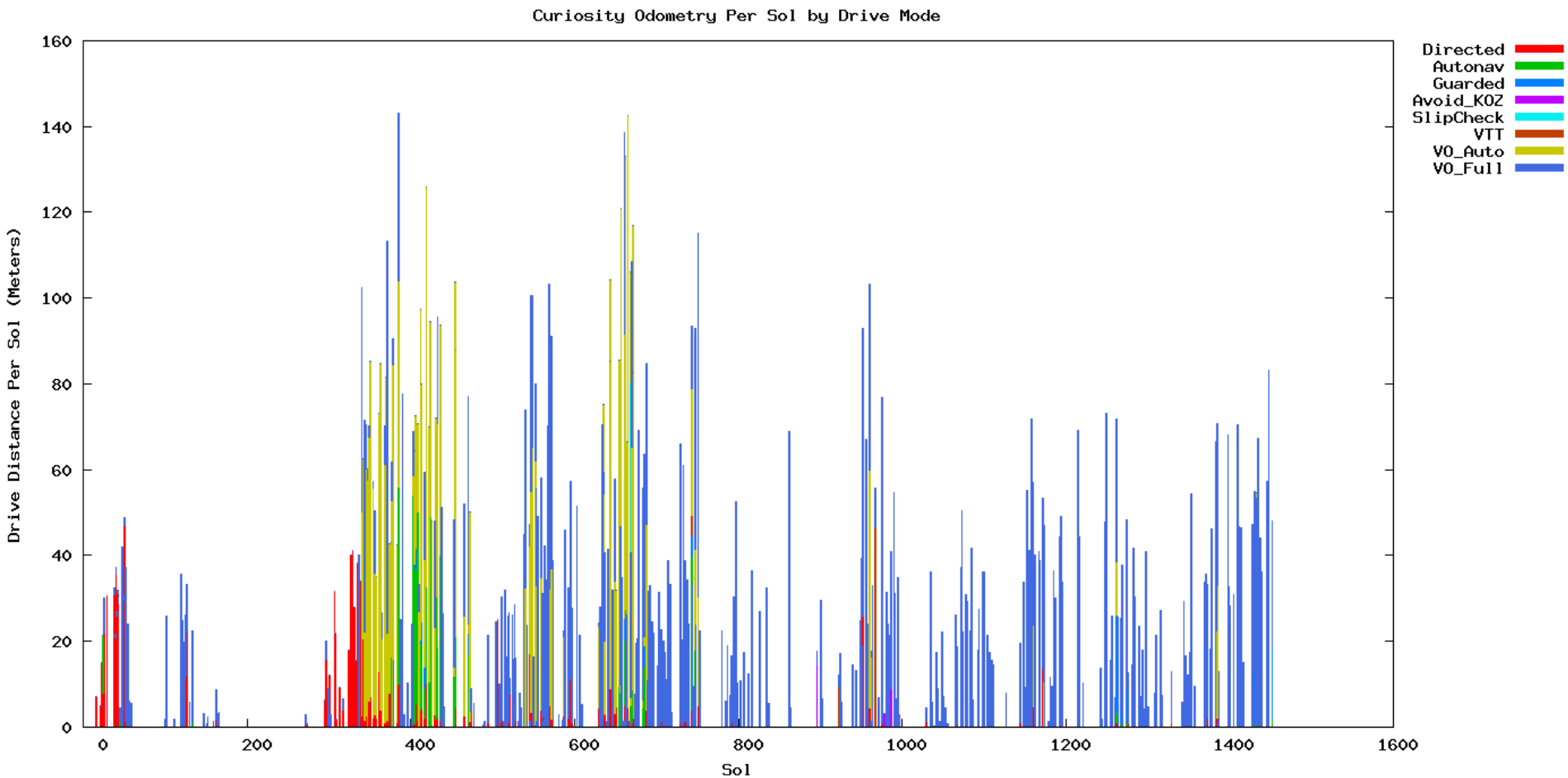


Unfortunately, the geometric lens models for the Navcams created before launch had poor stereo performance



Sol 201: Backup Navcams

- It was ultimately determined that the **cameras rotated slightly, but *predictably*, depending on the current temperature**
- We developed a novel re-calibration procedure, and generated new models at 4 temperatures
- Ground software was updated to use the current temperature
- R10 flight software was patched to read the current temperature and use the correct camera models by command to restore onboard autonomous imaging capabilities
- R11 flight software was enhanced to support temperature-varying camera models autonomously



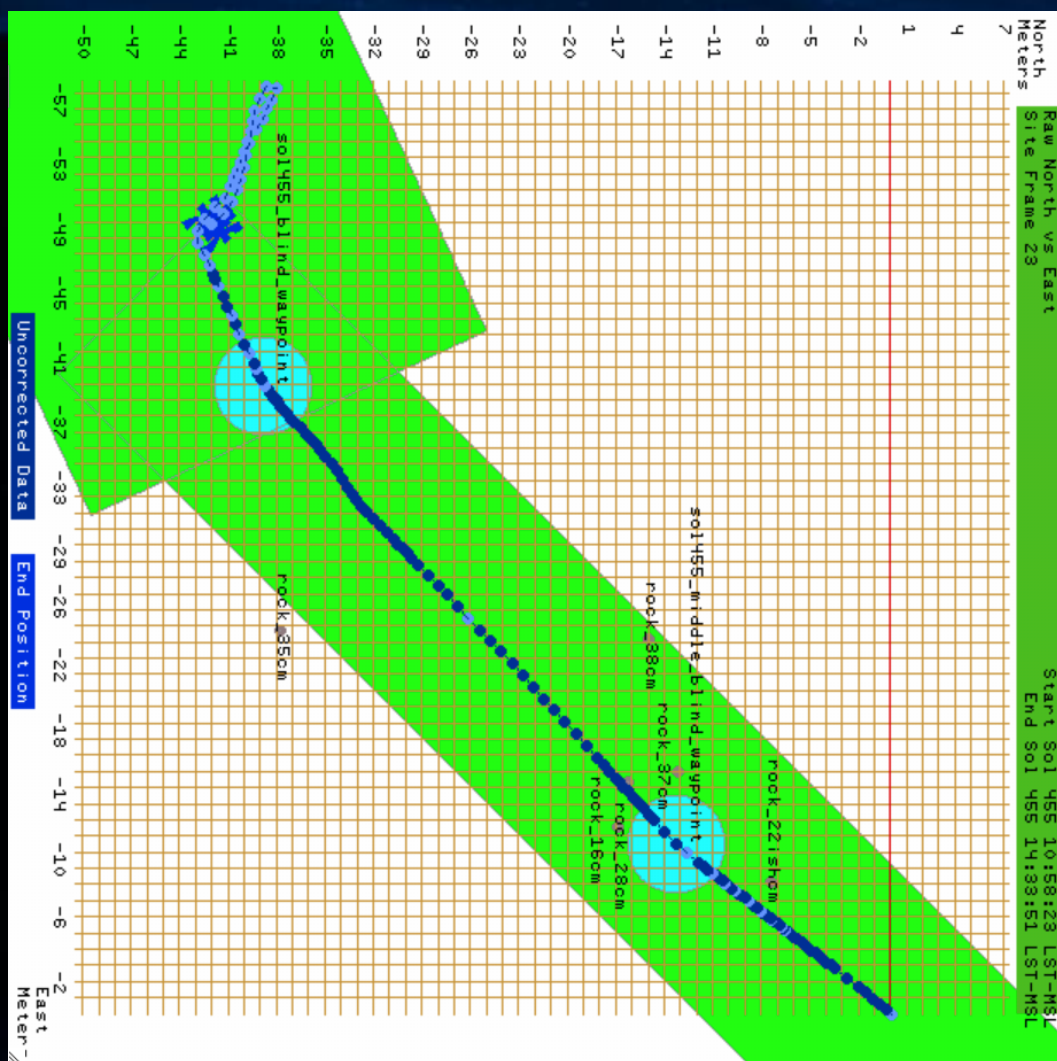


On sol 455, Curiosity Tried Multi-sol Driving again

- Multi-sol driving succeeded on sols 435-436!
- But the second try was halted by a drive stall, and interesting D* behavior on the first day, sol 455.



On sol 455, Curiosity encountered a small crater and began to drive around it



Small light blue dots represent the imaging steps



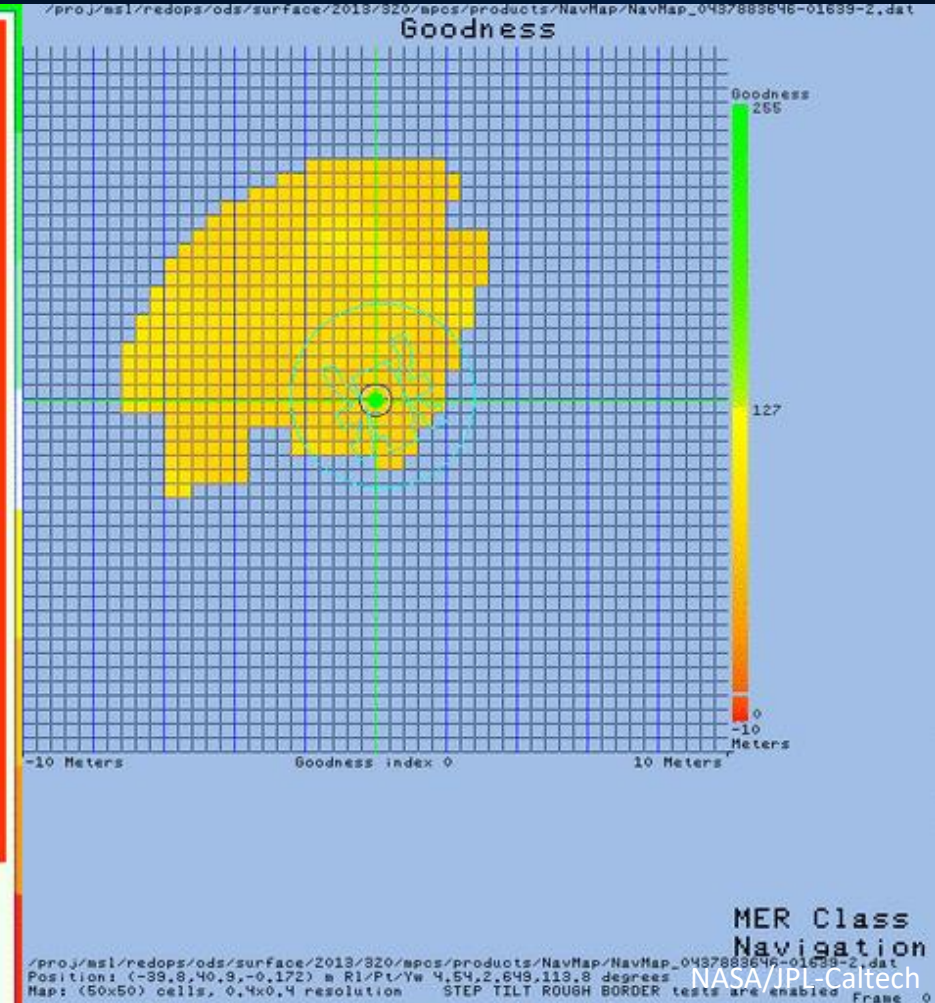
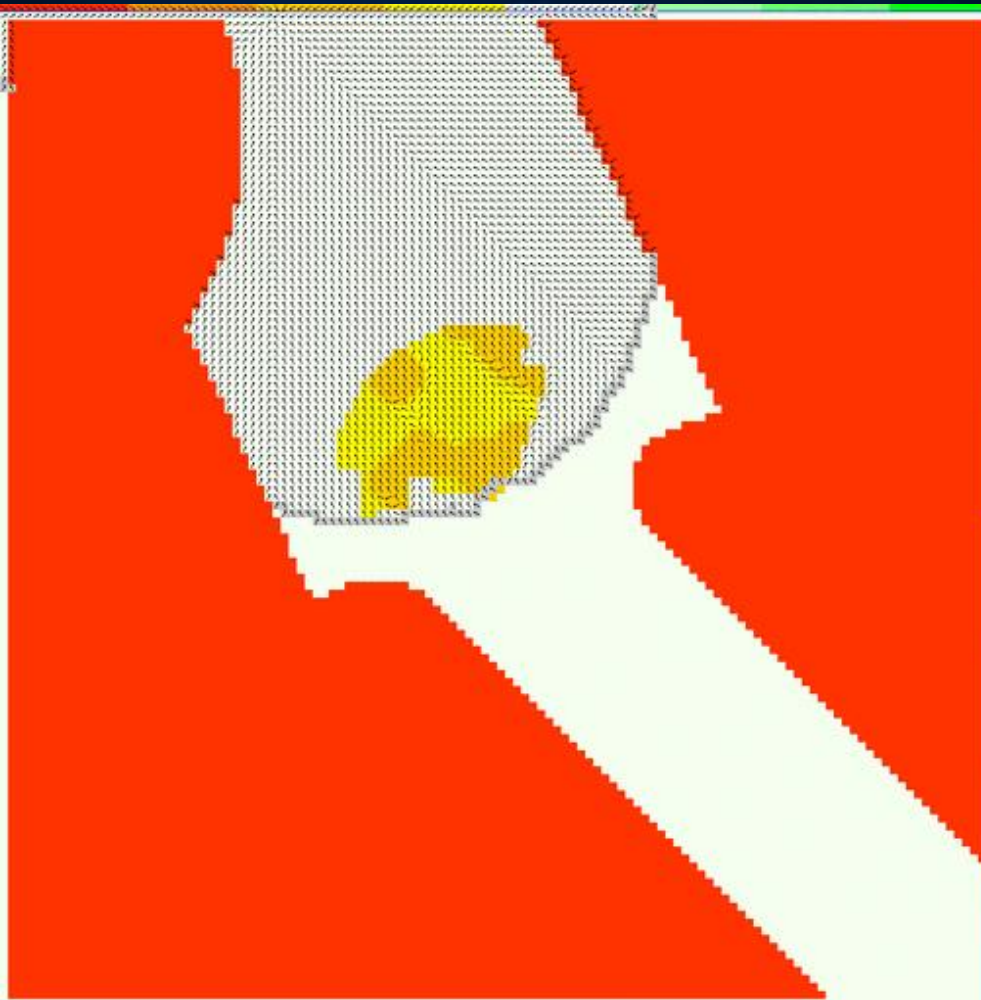
A Rover's-eye view of the Autonomous Portion of the sol 455 drive



11:59:02___./ImgImageLocoN1_0437883156-15288-1.pds

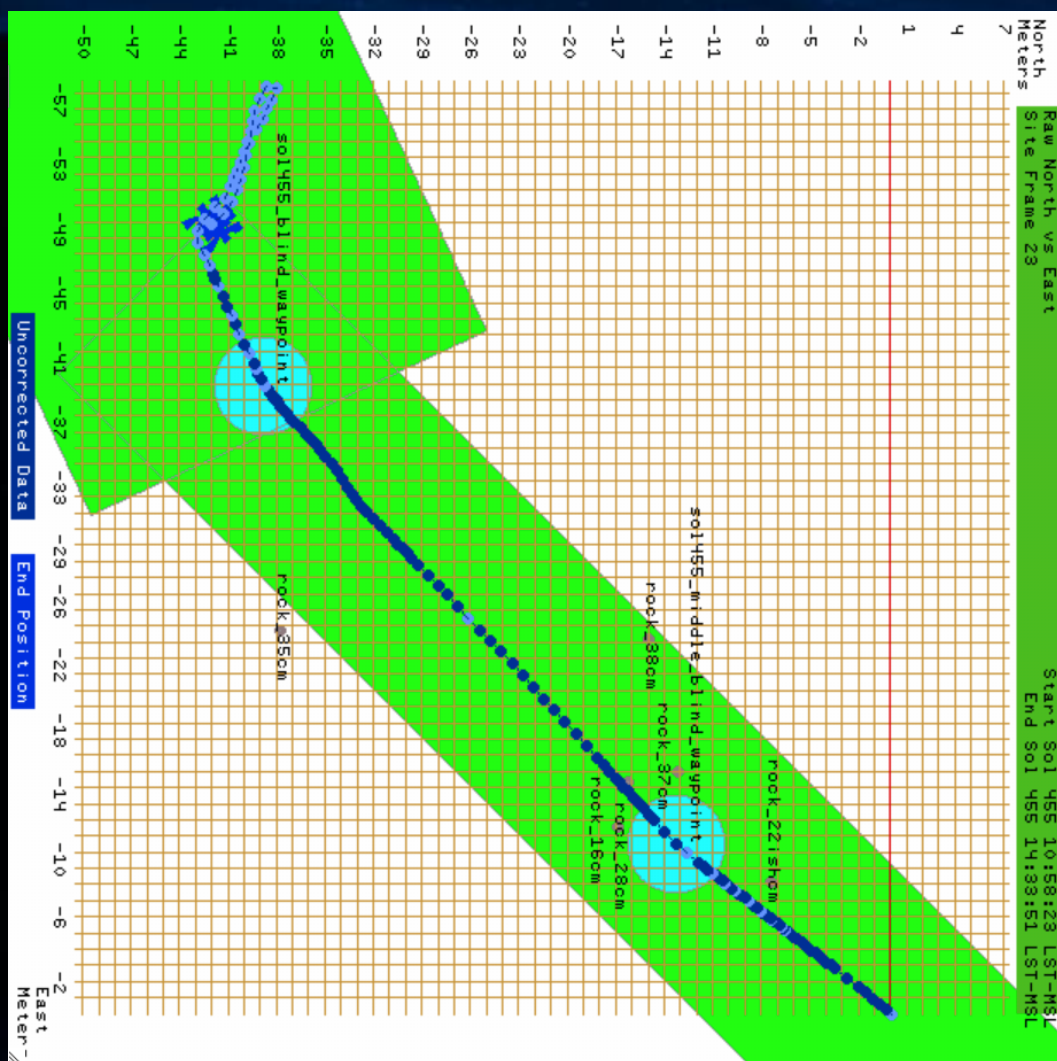


Then, boxed in by Keepin Zones, D* tried backtracking!





On sol 455, Curiosity encountered a small crater and began to drive around it

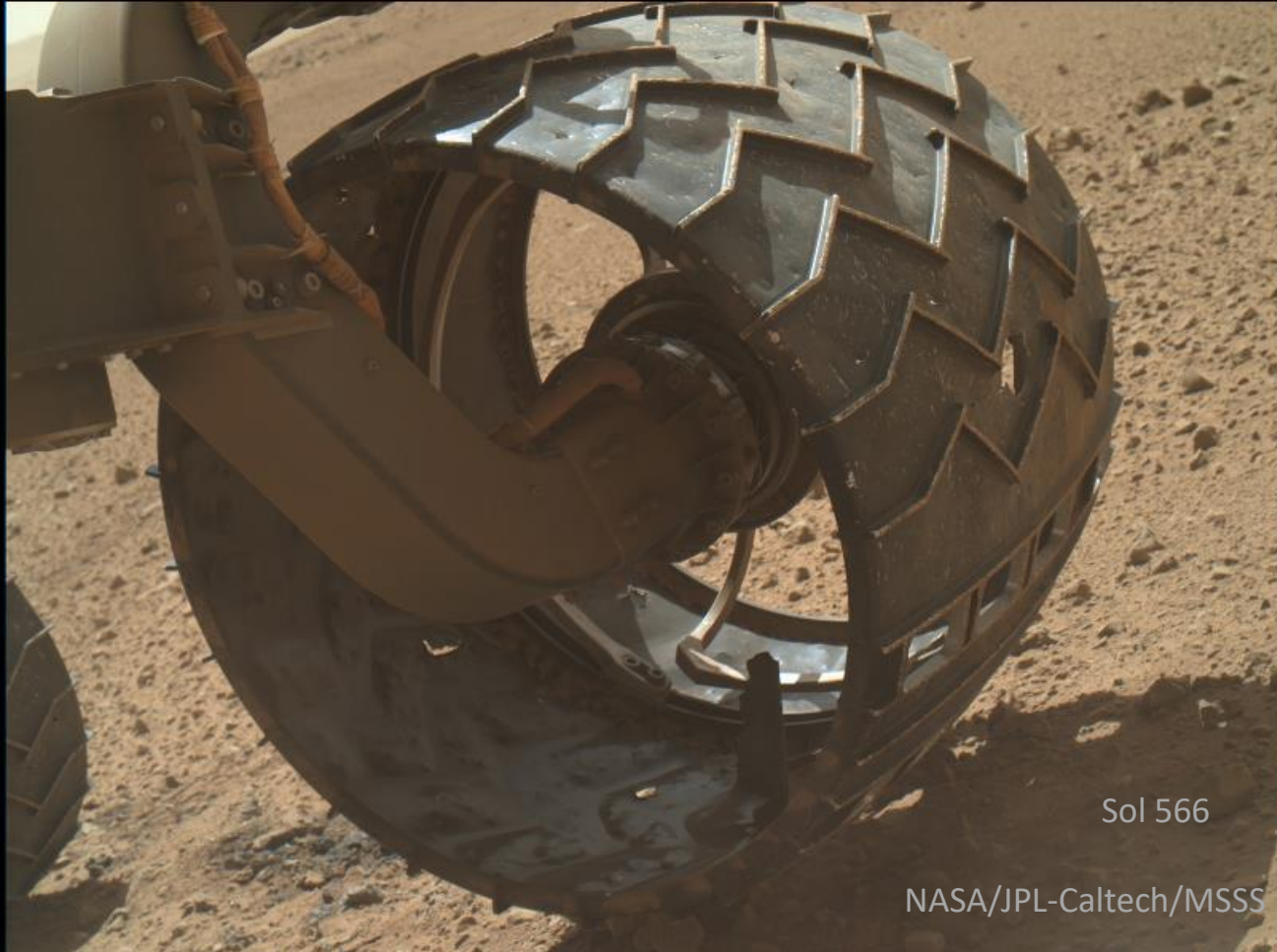


Small light blue dots represent the imaging steps



Sol 465: Wheel Wear

- We started to notice unusual amount of wear in our wheels

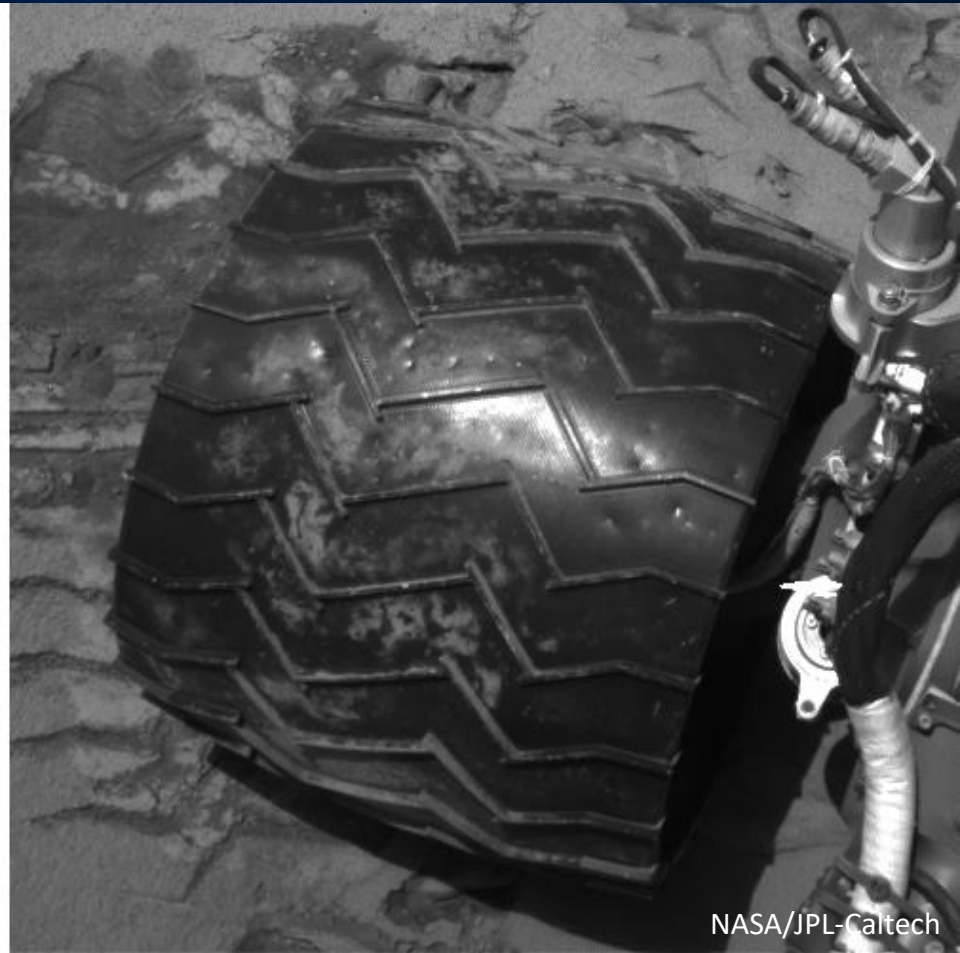




Sols 15-59: Before and After

Sol 15

Sol 60



Minor denting by small sharp rocks



Sols 60-309: Before and After

Sol 60

Sol 296



(No driving between sols 60-99, sols 167-271 and other smaller time windows)



Sols 313-396: Before and After

Sol 297

Sol 402



*(No driving between sols 310-312 and sols 397-401;
Wheel in partial image at sol 313 looks like that at sol 297)*



Sols 402-477: Before and After

Sol 402

Sol 477



Severe denting by grouser-sized rocks

Terrain

Map courtesy of Fred Calef

We do not see 1:1 correlation between global map and local terrain

Murray Buttes

3/12/2020

Kilometers

0 0.5 1 2 3 63 4

Sol 60
Bradbury
Landing

Yellowknife
Bay

Sol 296

Darwin

Sol 402

Cooperstown

465

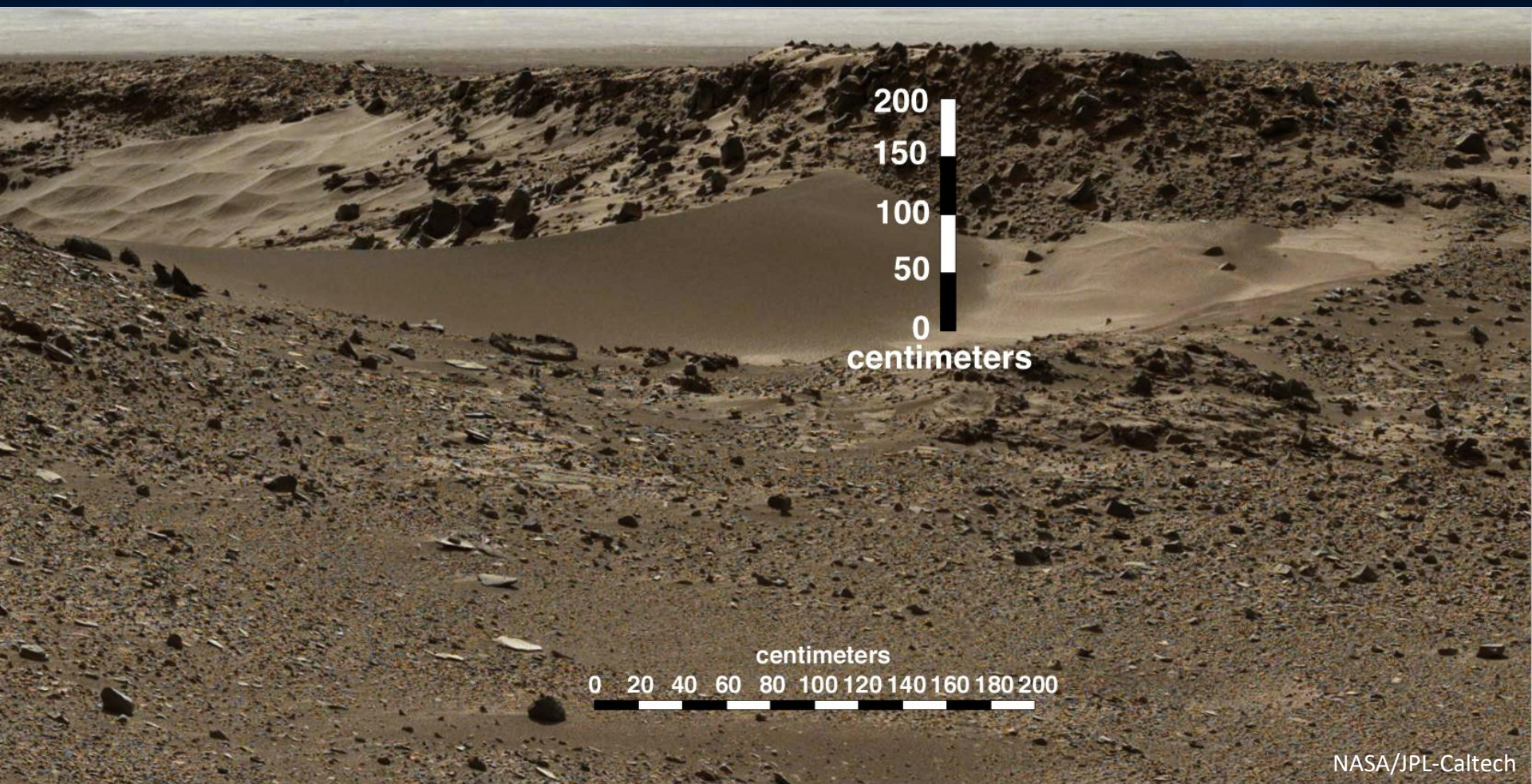
KMS_9

FC_9

- ★ Bradbury Landing
- ★ Current Position
- ▲ Geologic Waypoints
- Actual Traverse
- Rapid Transit Route
- Geologic Units
- MOD_UNITS
- ALF
- Cratered Surface
- Eolian
- Bright-toned Fractured
- Ridged Unit
- Smooth-Hummocky
- Striated 36



Sol 533-535: Dingo Gap



NASA/JPL-Caltech



Sol 533-535: Dingo Gap



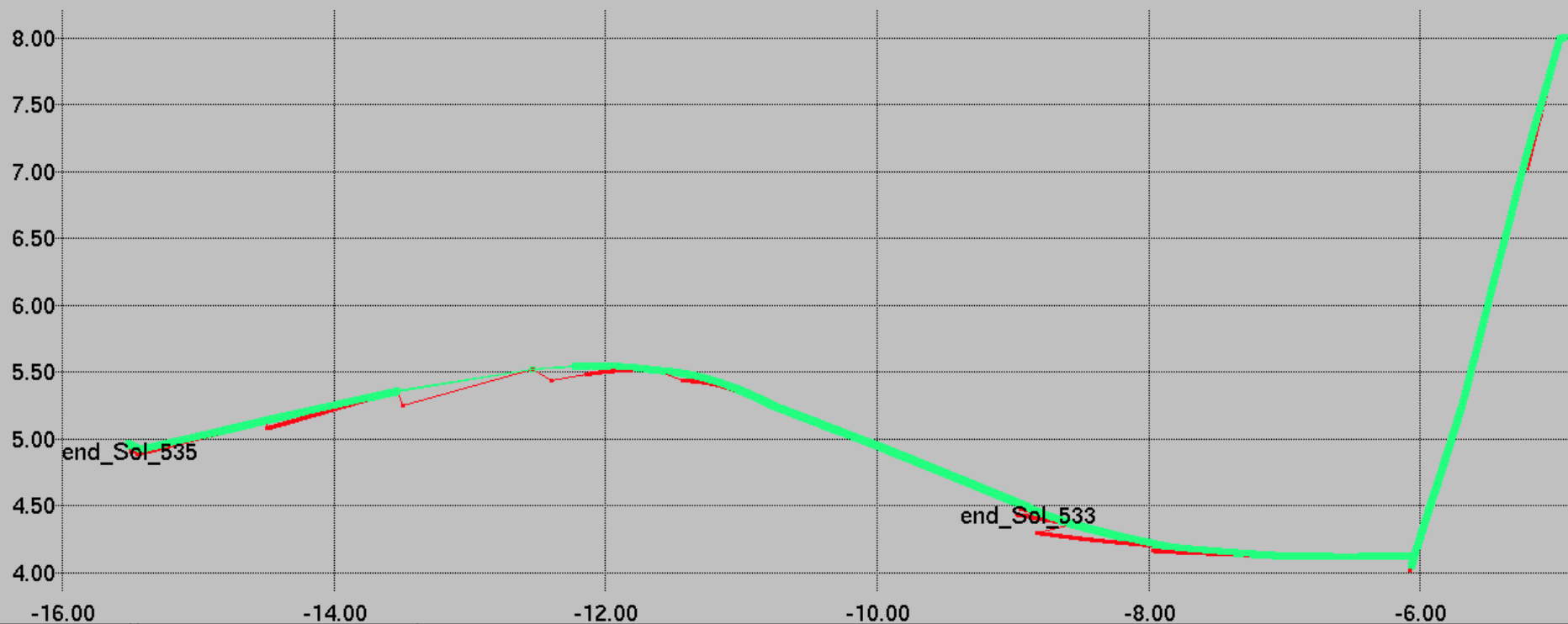
NASA/JPL-Caltech



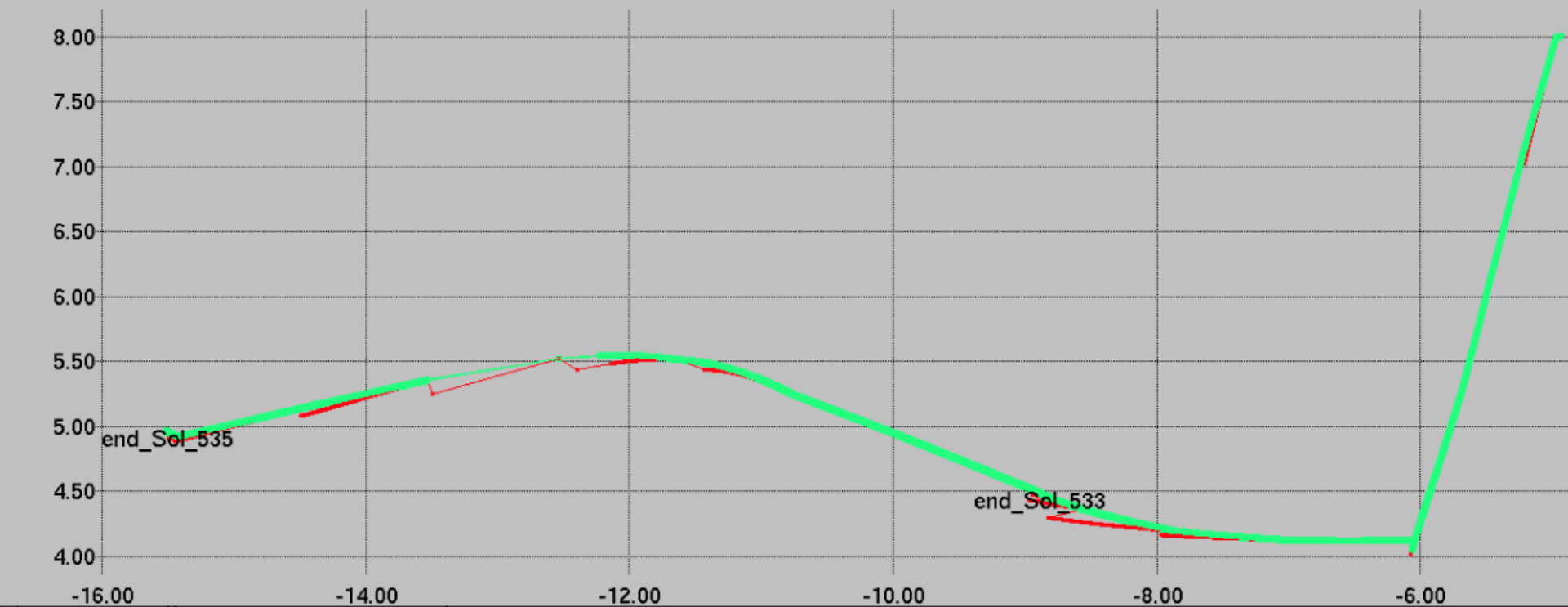
Sol 533-535: Dingo Gap

[e](#) [Hardcopy](#) [About](#)
north (Meters)

Corr_east vs Corr_north from Sol 533 11:30:14 to Sol 535 13:39:57 LST-MSL



Corr_east vs Corr_north from Sol 533 11:30:14 to Sol 535 13:39:57 LST-MSL



vo_site_pointing





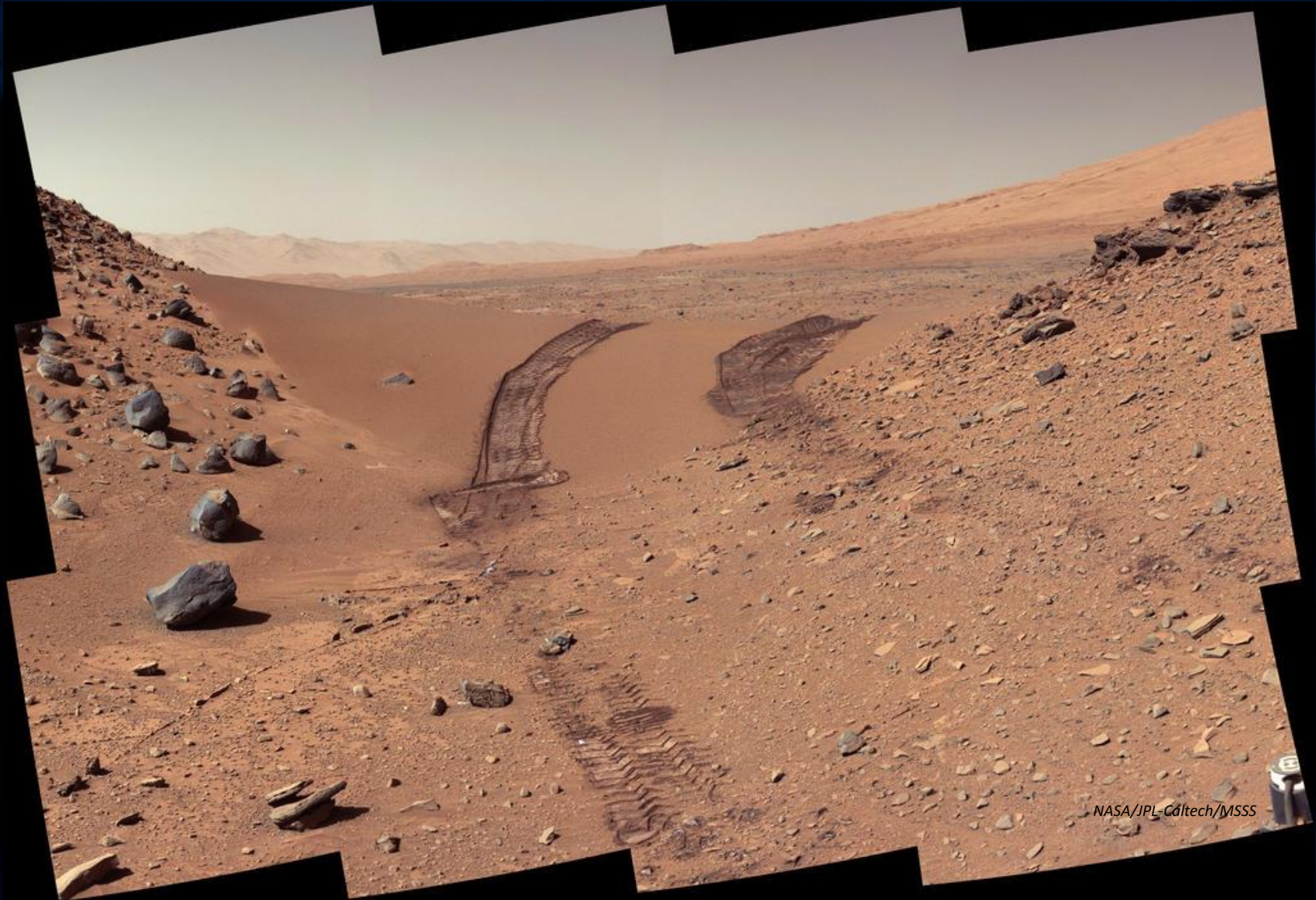
Sol 535: Climbing Over



NASA/JPL-Caltech

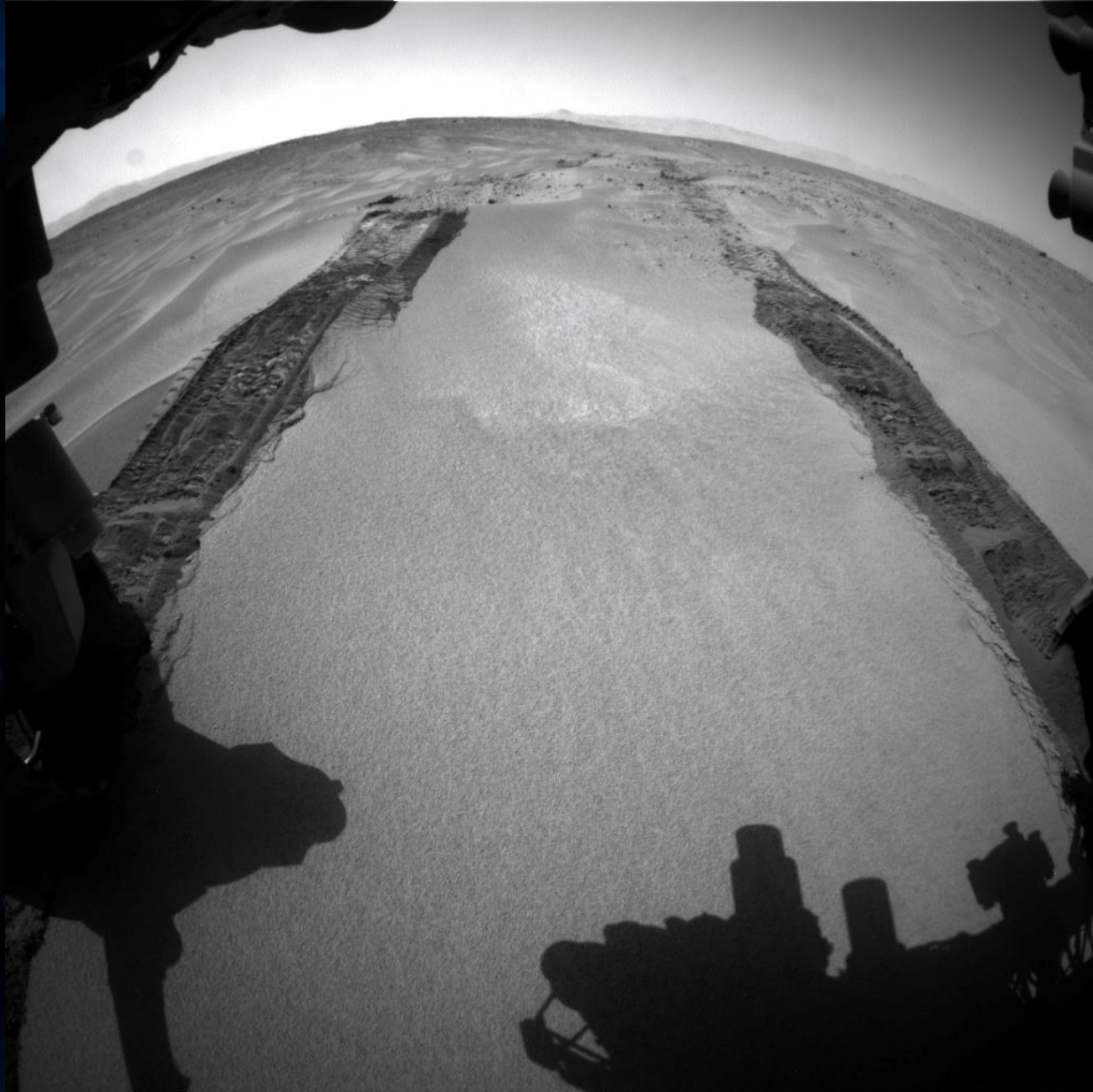


Sol 533-535: Dingo Gap



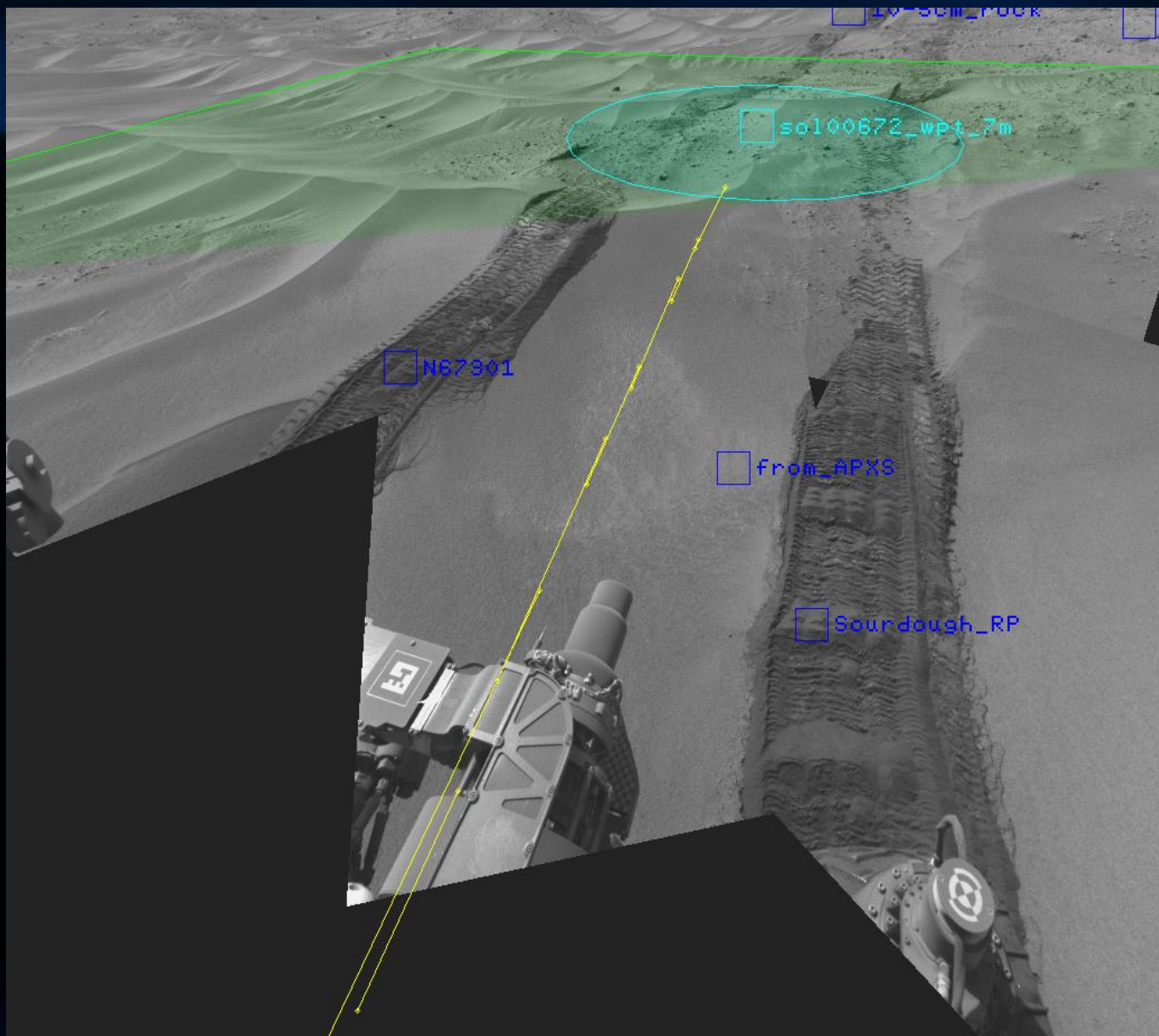


Sol 672: Partial Embedding





Sol 674: We're out, thanks to VO Auto!



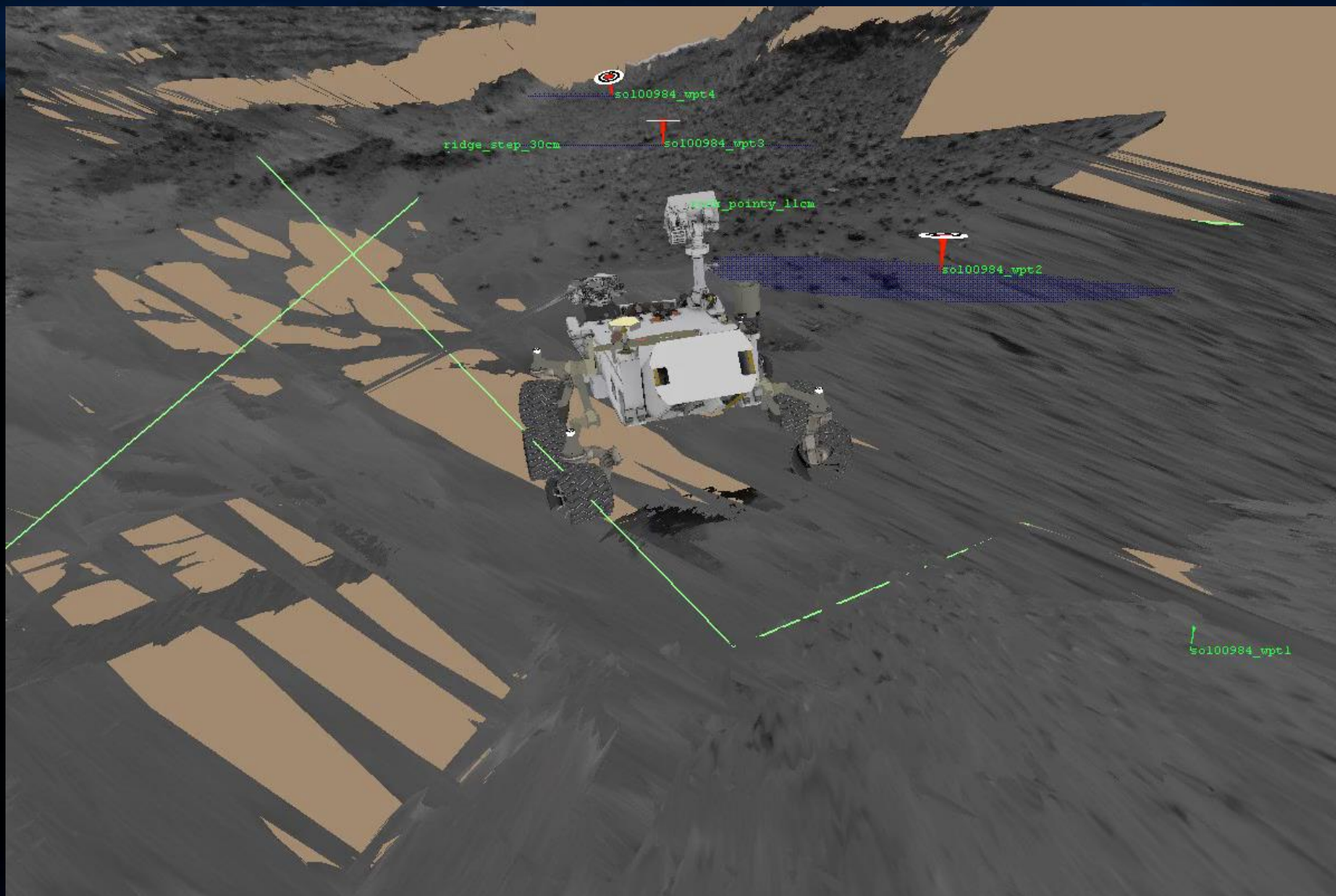


Sol 674: Tracks look better on the way out





Sol 984: Logan Pass, Slippery Slope



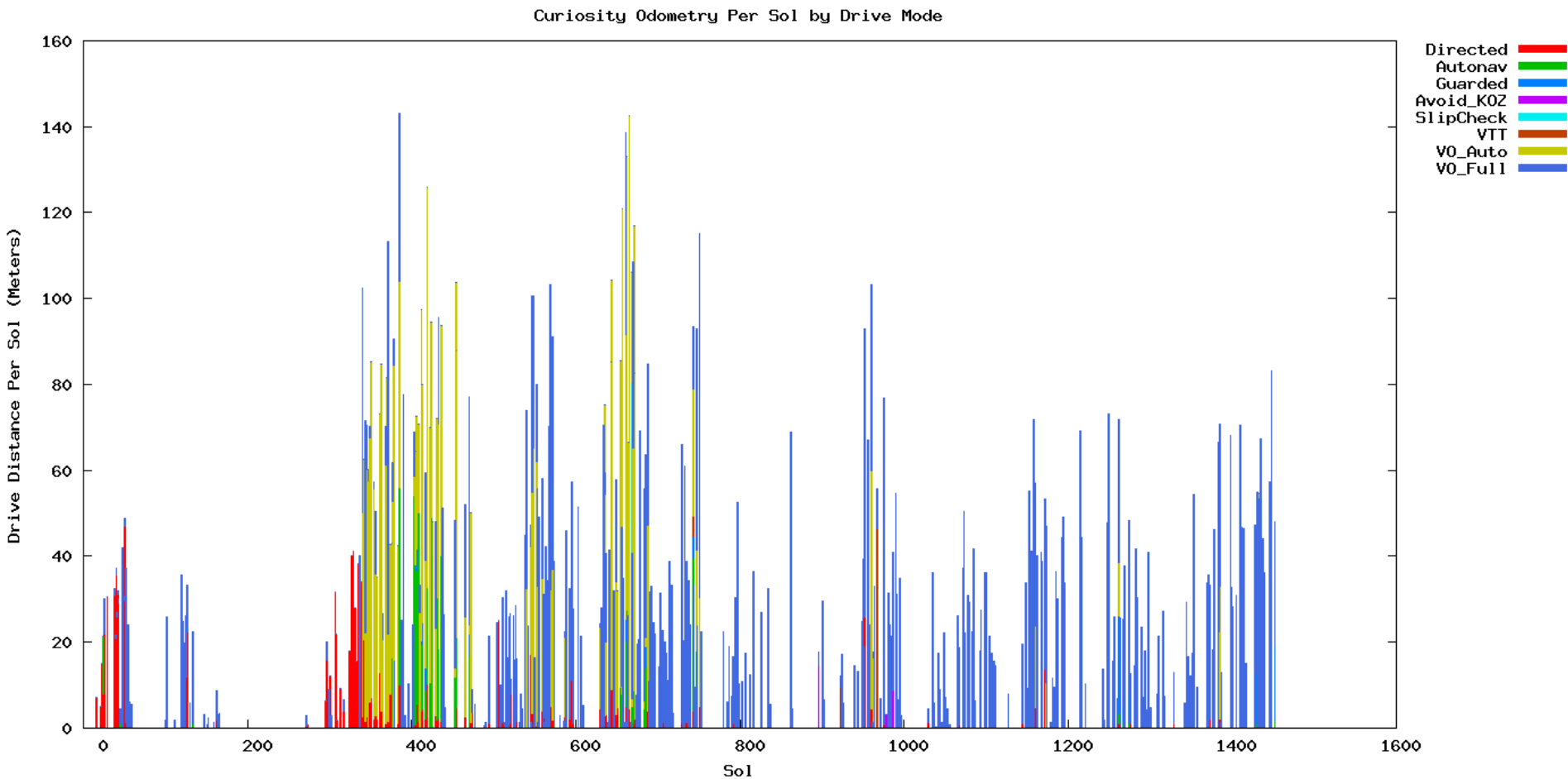


Statistics through sol 1450

Artist's Concept. NASA/JPL-Caltech

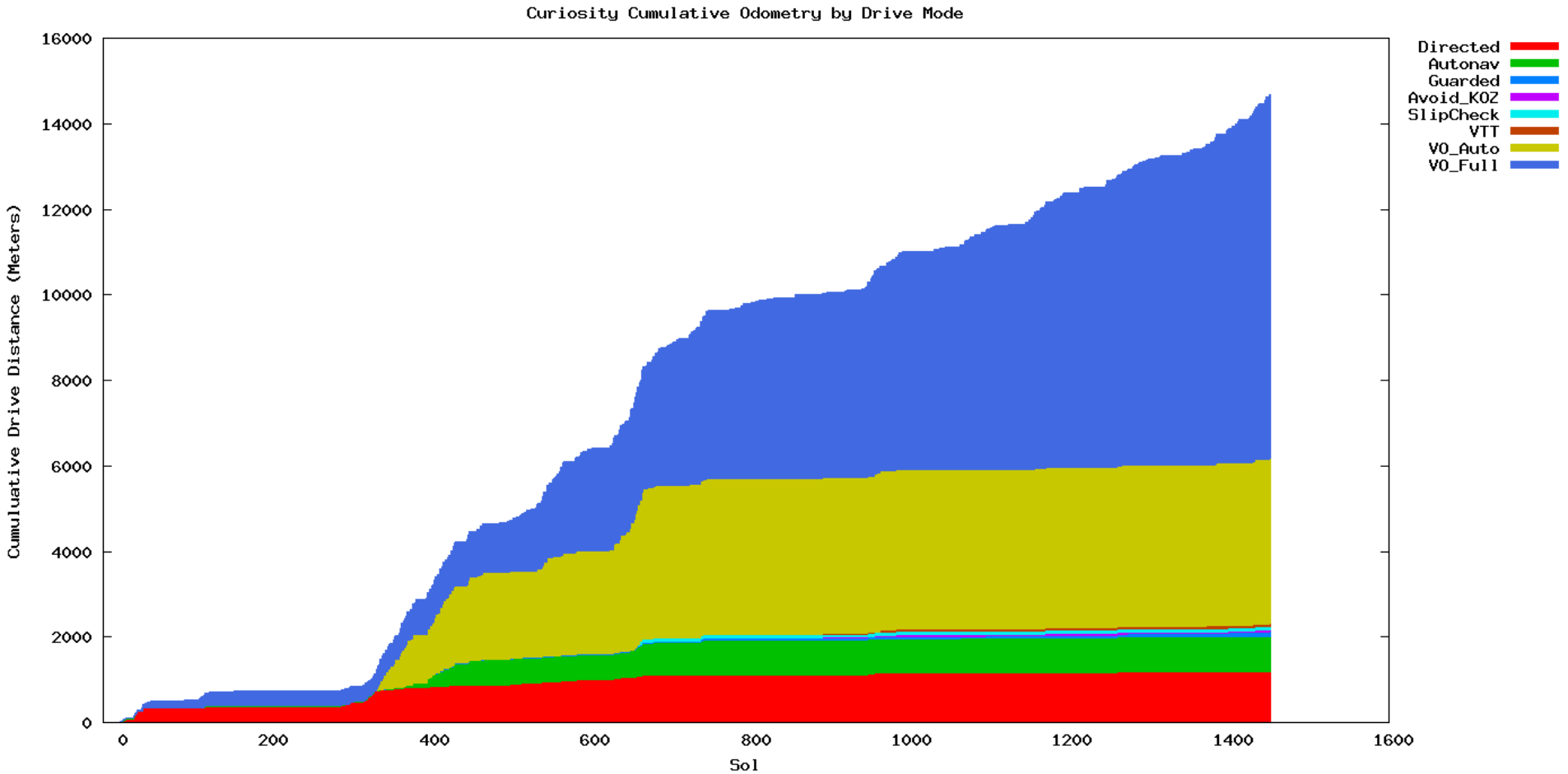


Curiosity Odometry Per Sol



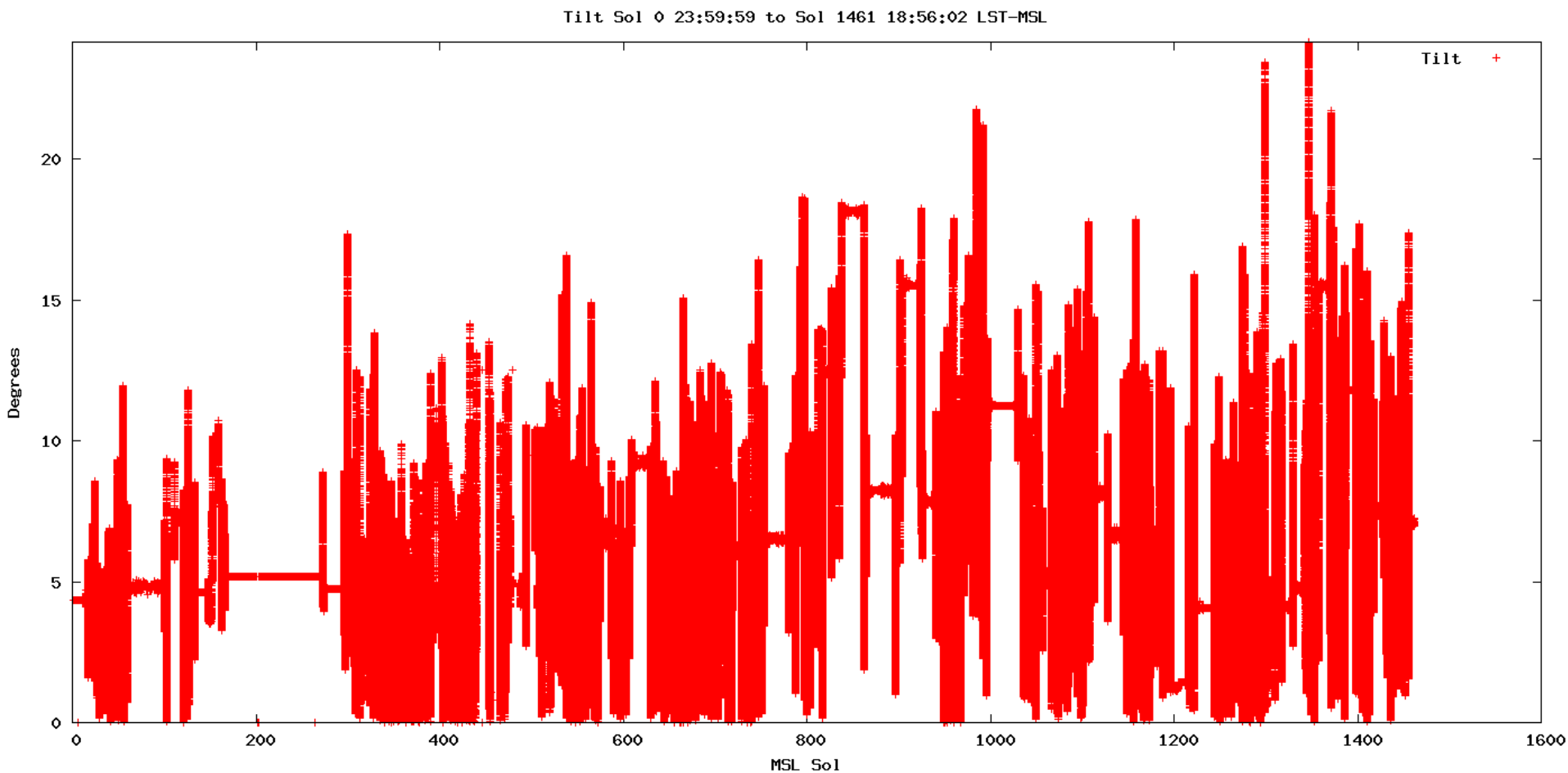


Curiosity Cumulative Odometry



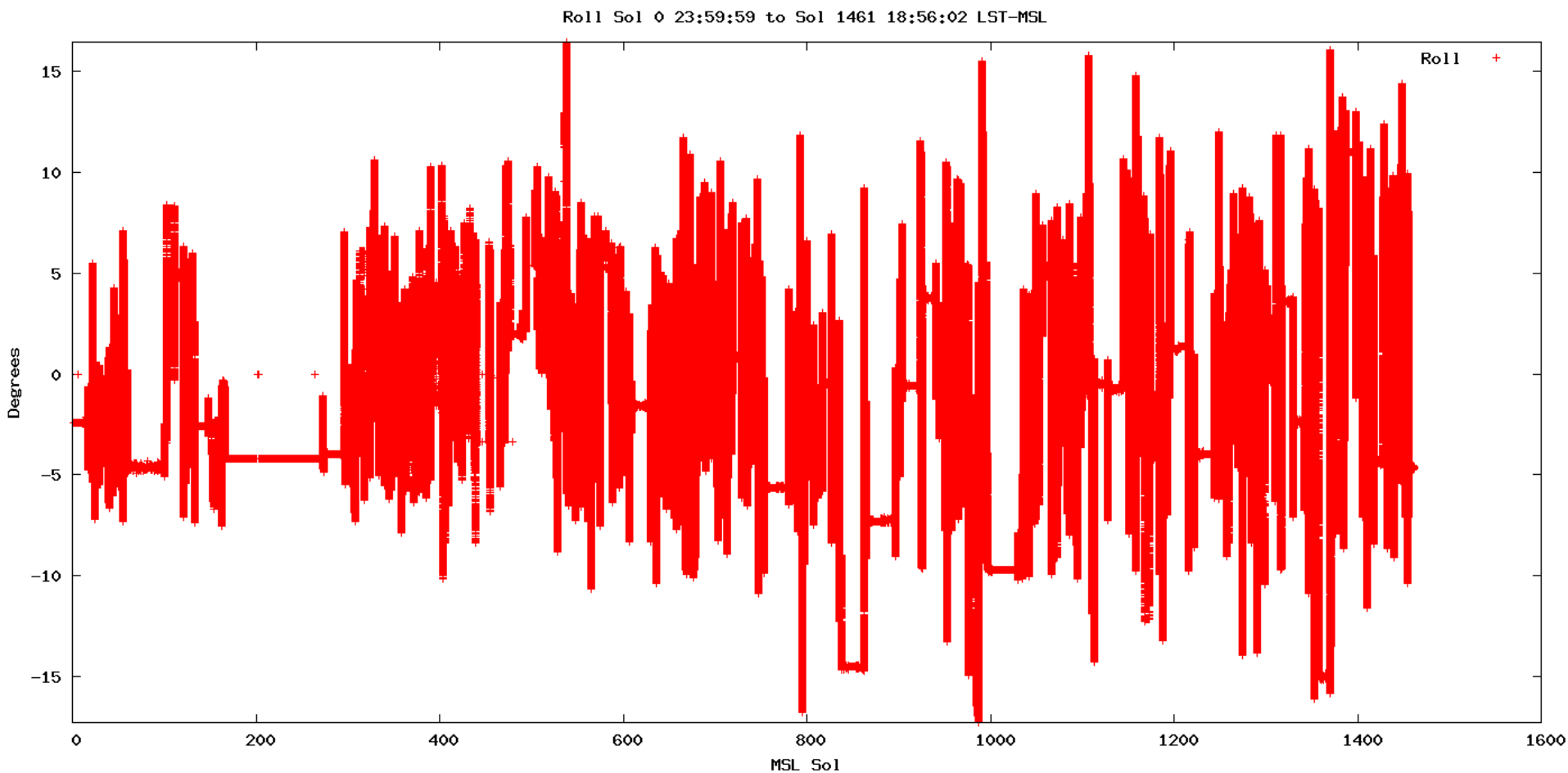


Curiosity Tilt Per Sol (through Sol 1461)



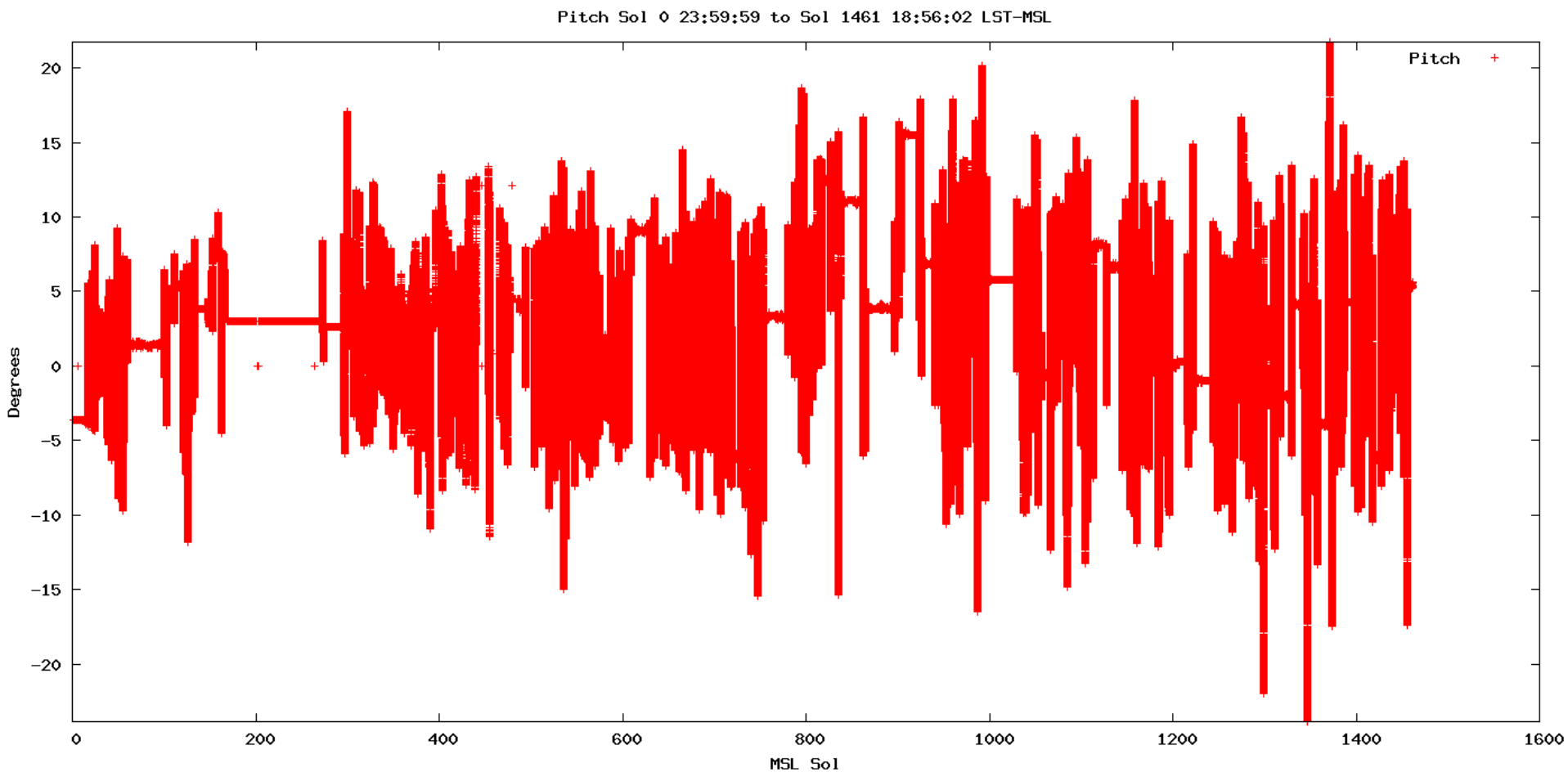


Curiosity Roll through Sol 1461



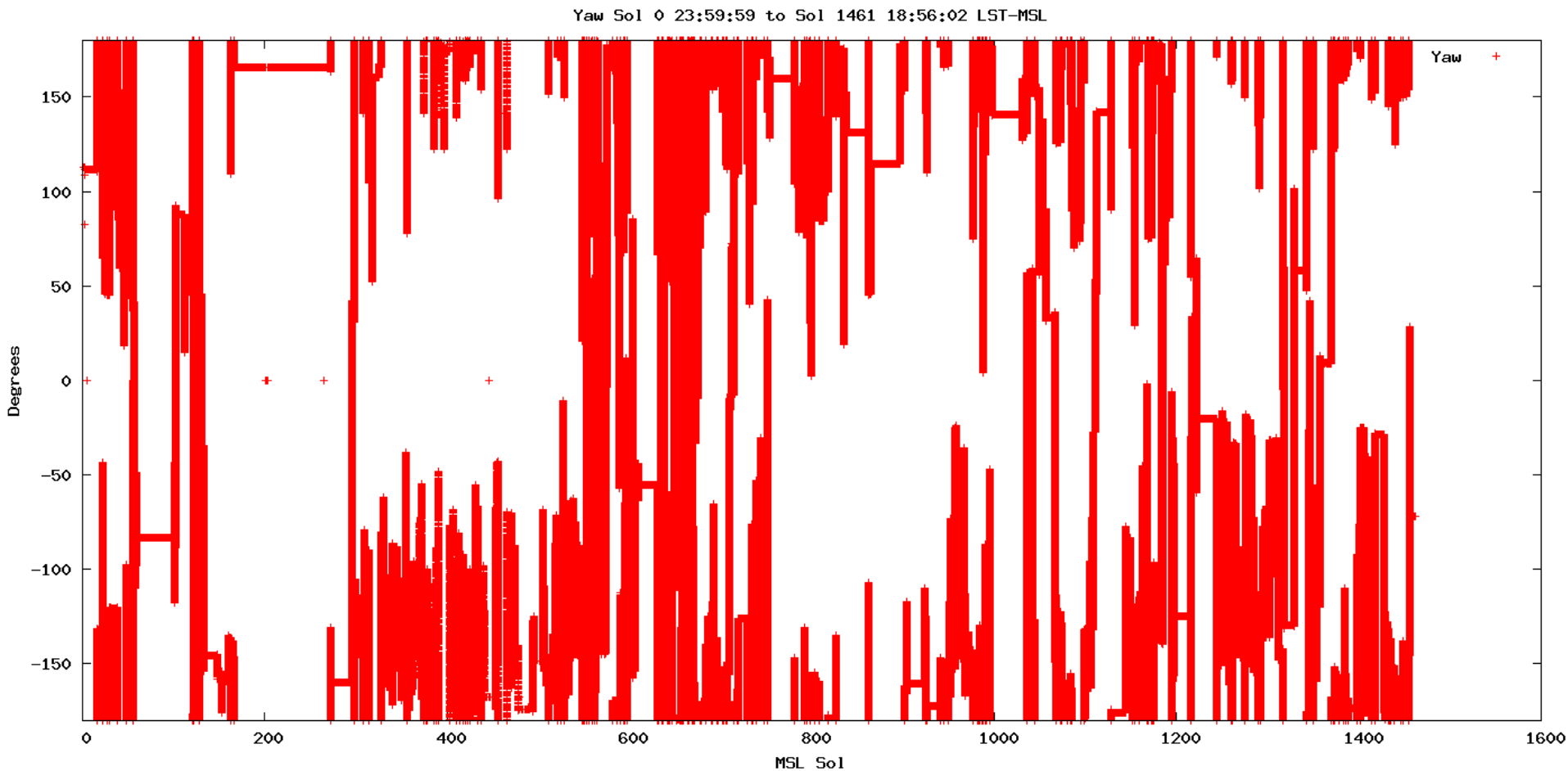


Curiosity Pitch through Sol 1461





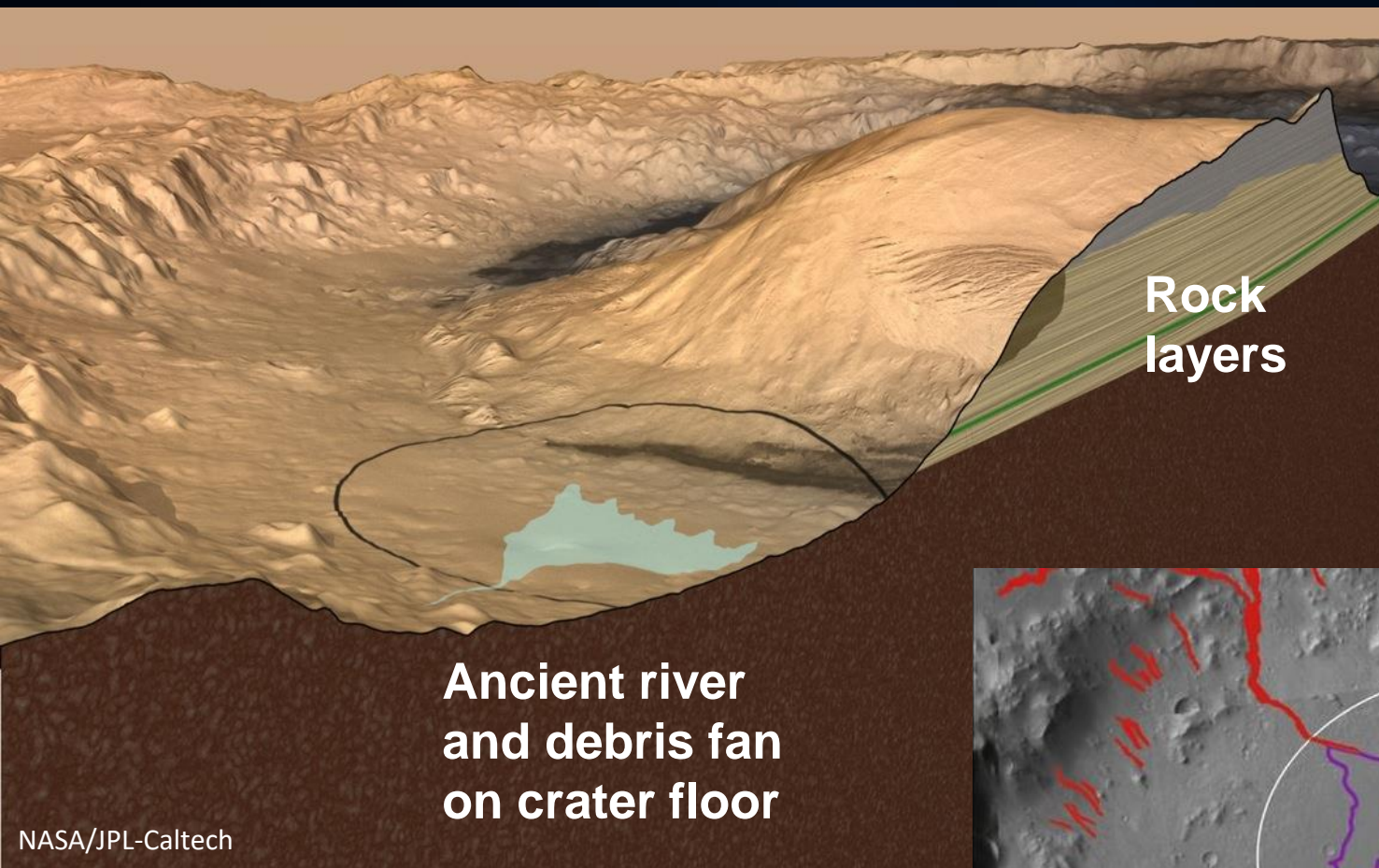
Curiosity Yaw through Sol 1461





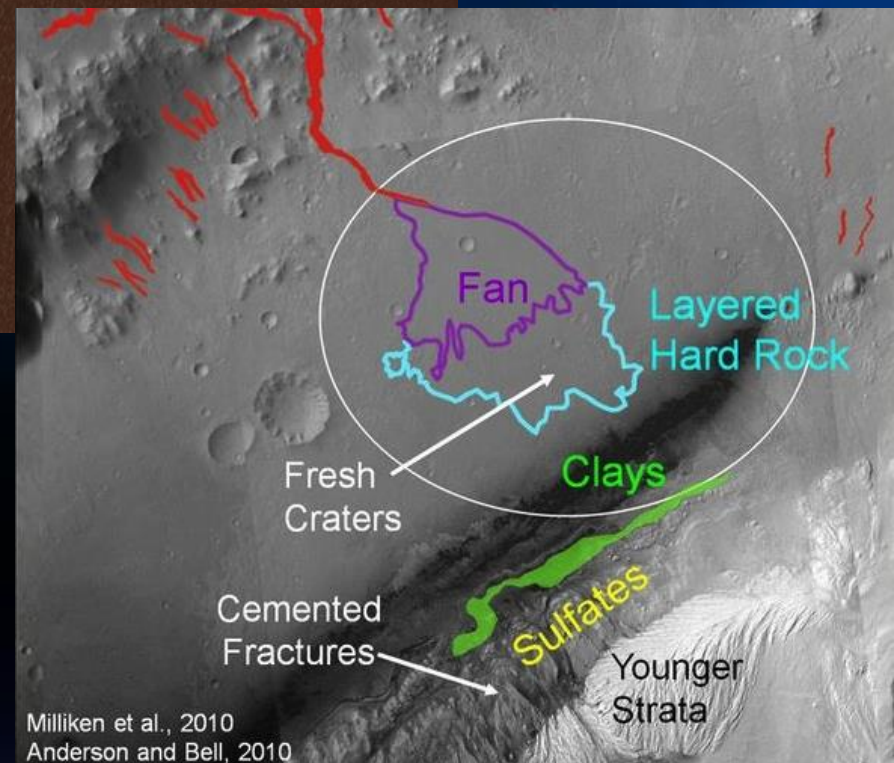
WDC? Science!

Artist's Concept. NASA/JPL-Caltech



Water-Related Geology and Minerals around Mount Sharp

CMU 2016



**HUMMOCKY
PLAINS**

**BEDDED
FRACTURED UNIT**

**Bradbury
Landing**

Rocknest

**Yellowknife
Bay**

Rover Tracks

Curiosity

**CRATERED
UNIT**



NASA/JPL-Caltech/Univ. of Arizona



EMC 2016

**Curiosity and its tracks captured by
HiRISE on the Mars Reconnaissance Orbiter**



NASA/JPL-Caltech/MSSS

**Rounded pebbles and sand in the conglomerate
“Link” indicate water flowed ankle to hip deep**

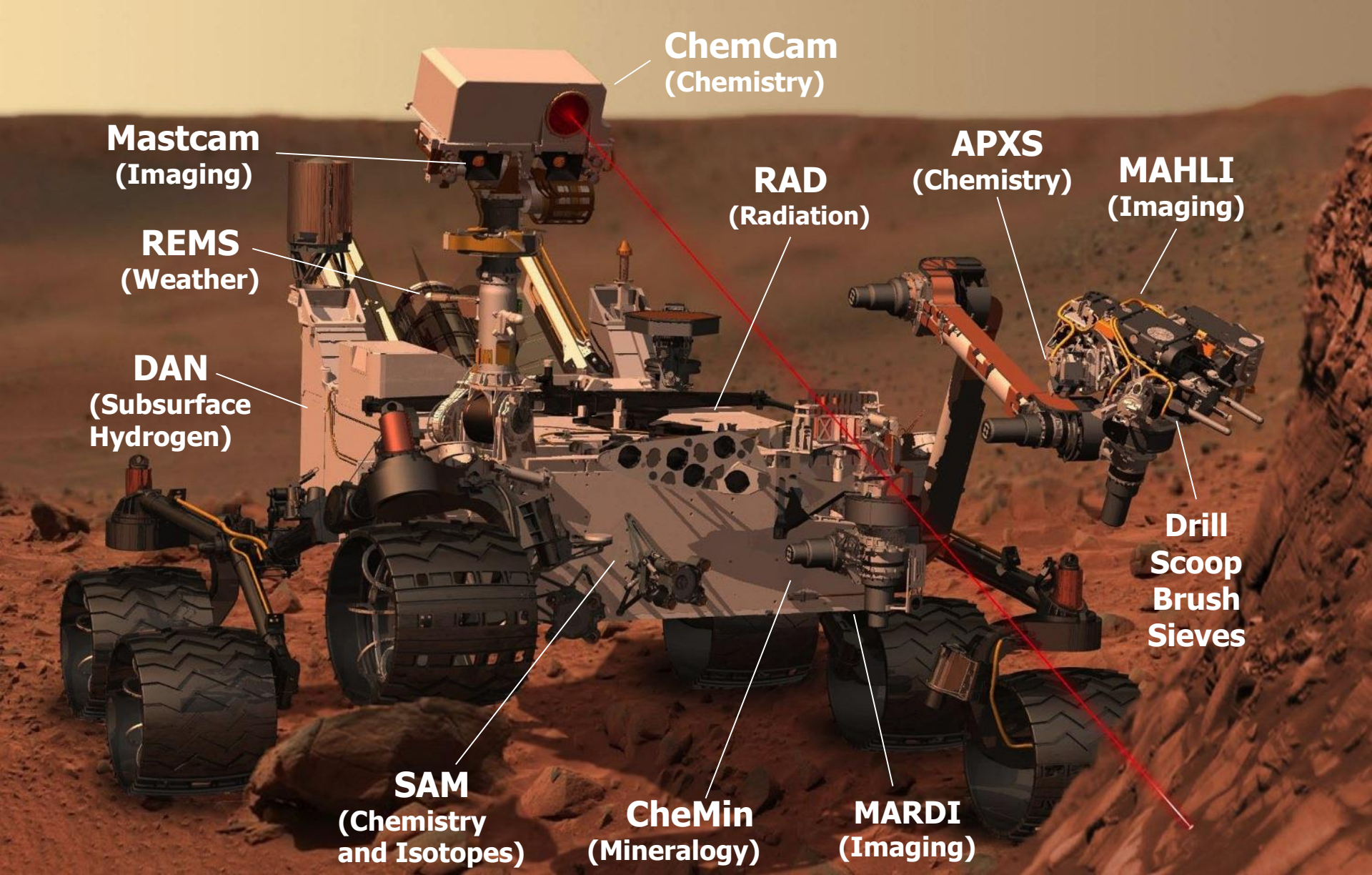


NASA/JPL-Caltech/MSSS

**Yellowknife Bay shows
a diversity of rock
types, fractures, and
veins**

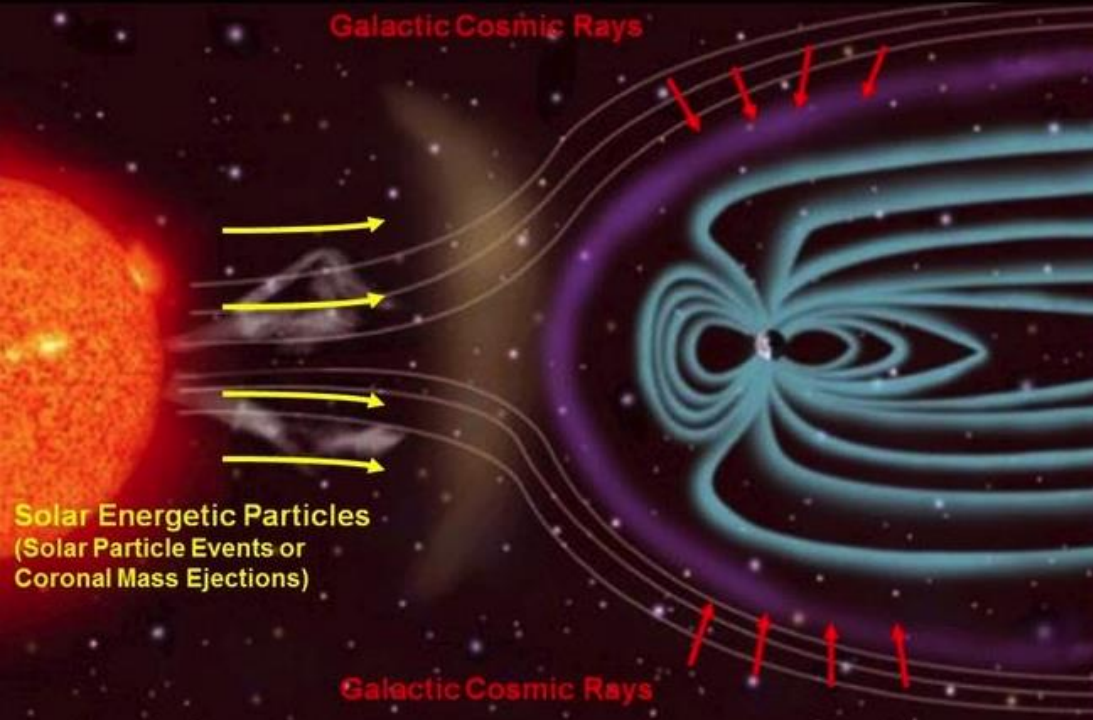


NASA/JPL-Caltech



Curiosity's Science Payload

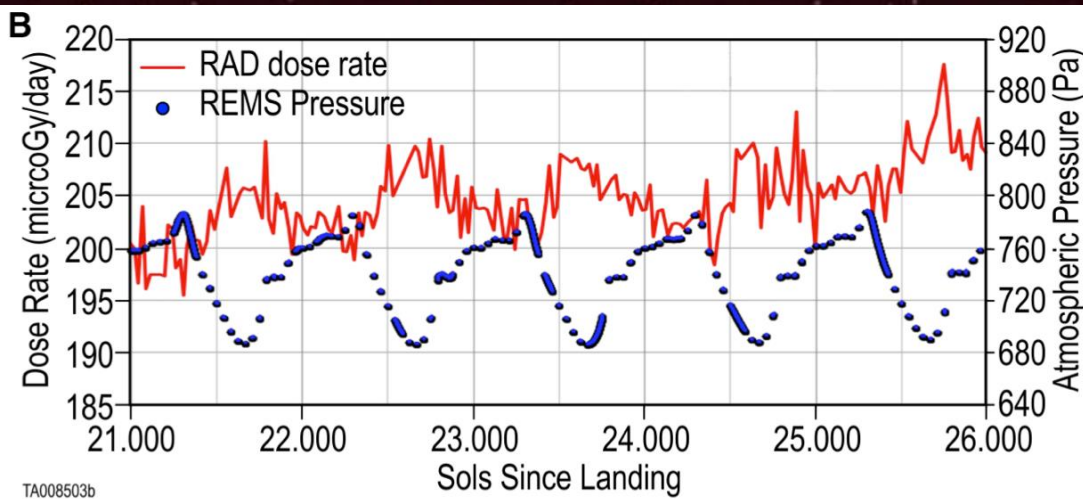
Artist's Concept. NASA/JPL-Caltech



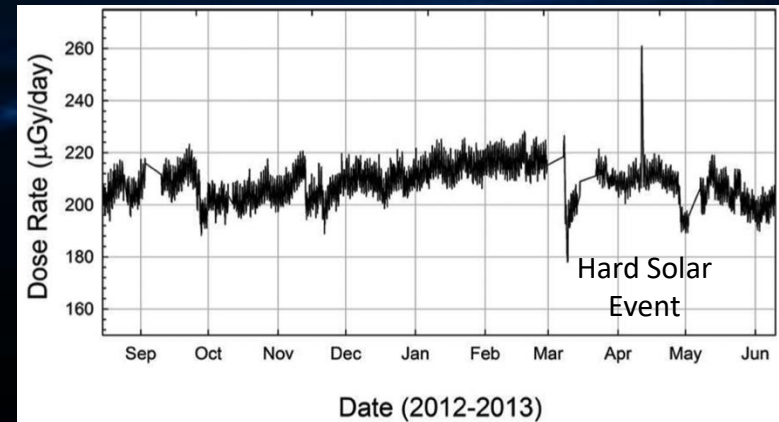
The RAD instrument measured the radiation flux from both galactic cosmic rays and solar energetic particles, in cruise and at Mars' surface

The surface dose rate is about half that measured in cruise

A crewed mission would receive ~1 Sievert of exposure in a trip to Mars with 500 sols on the surface



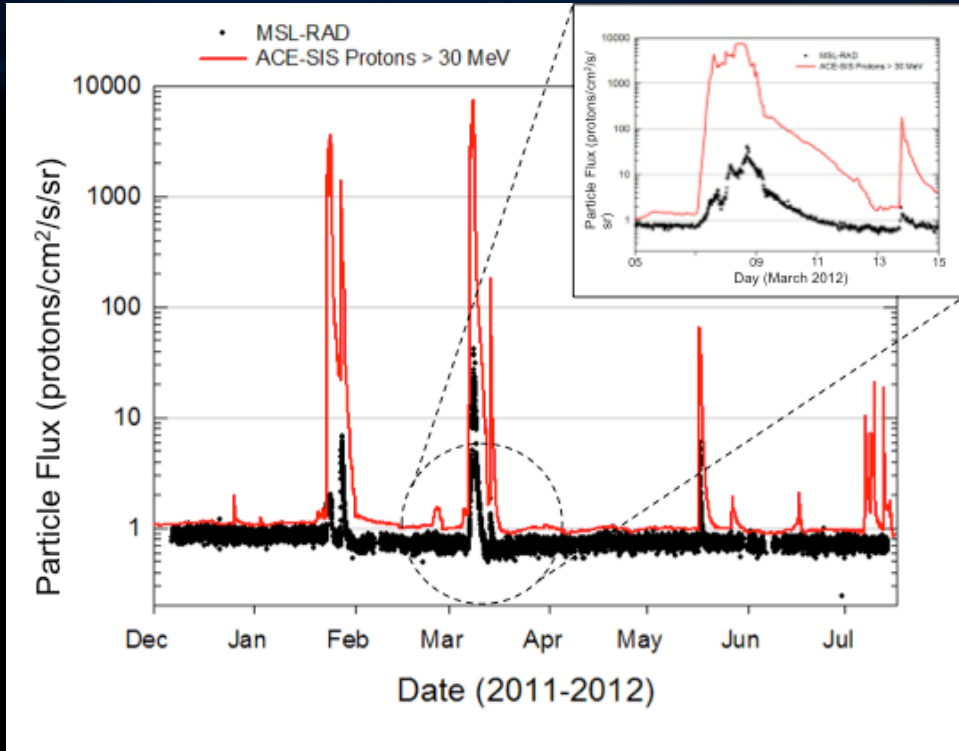
[Hassler et al., 2014]



Curiosity's Radiation Assessment Detector measures high-energy radiation



RAD & REMS



RAD observed galactic cosmic rays and five solar energetic particle events

RAD is now collecting the first measurements of the radiation environment on the surface of another planet

I get Mars weather reports from Twitter



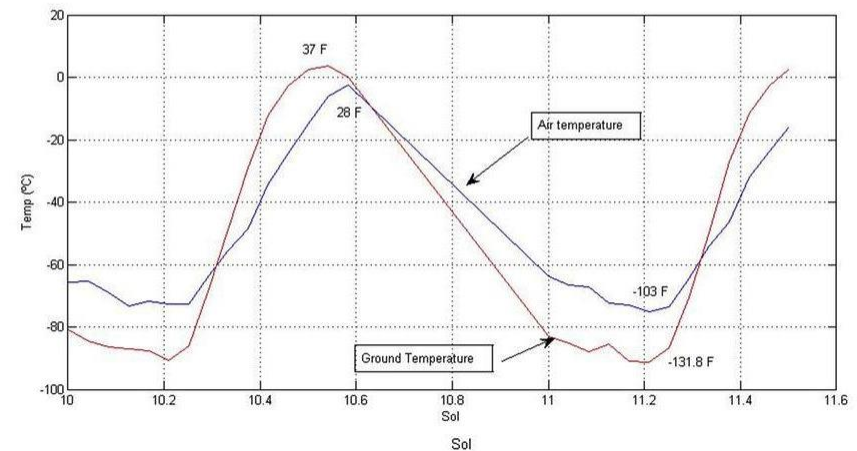
Mars Weather @MarsWxReport

Sol 76 (Oct 23, 2012): Sunny, high -1C/30F, low -72C/-97F, pressure higher at 7.91 hPa, wind E at 7.2kmh/4.5mph, daylight 6am-5pm

Expand

5h

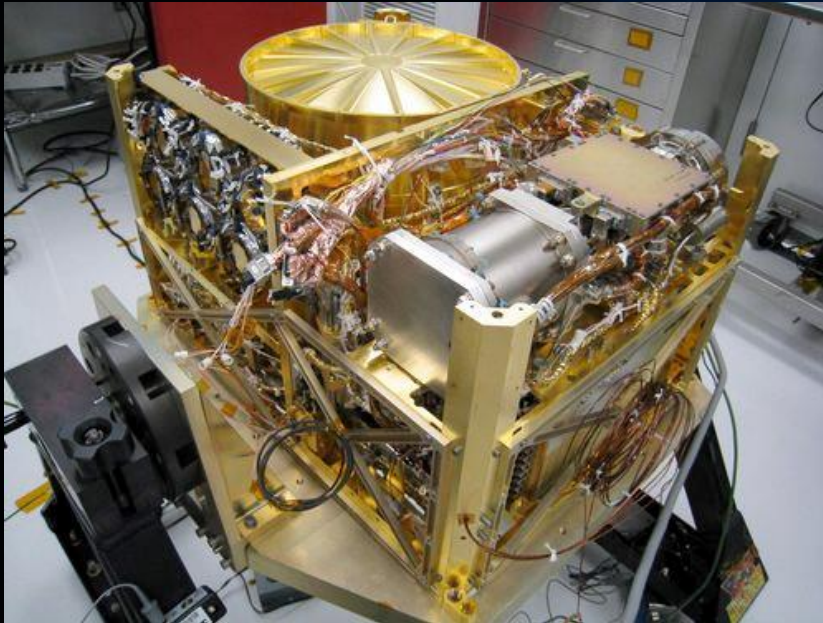
GROUND AND AIR TEMPERATURE SENSOR





SAM & CheMin

SAM instrument which takes up more than half the science payload on the rover

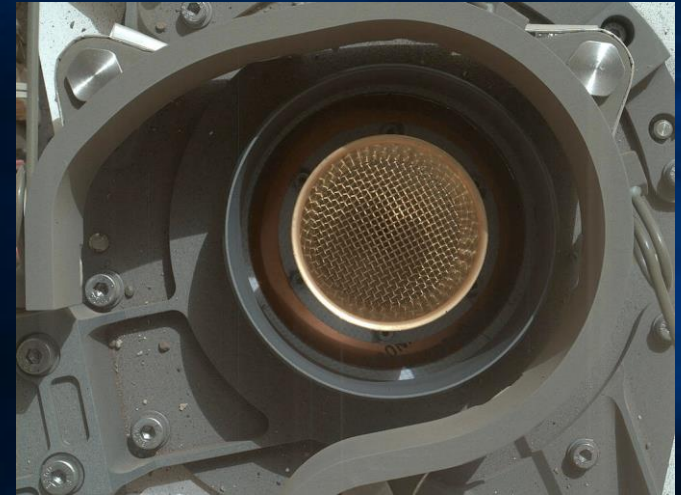


Sample Analysis at Mars (SAM) is the rover's Easy Bake Oven.

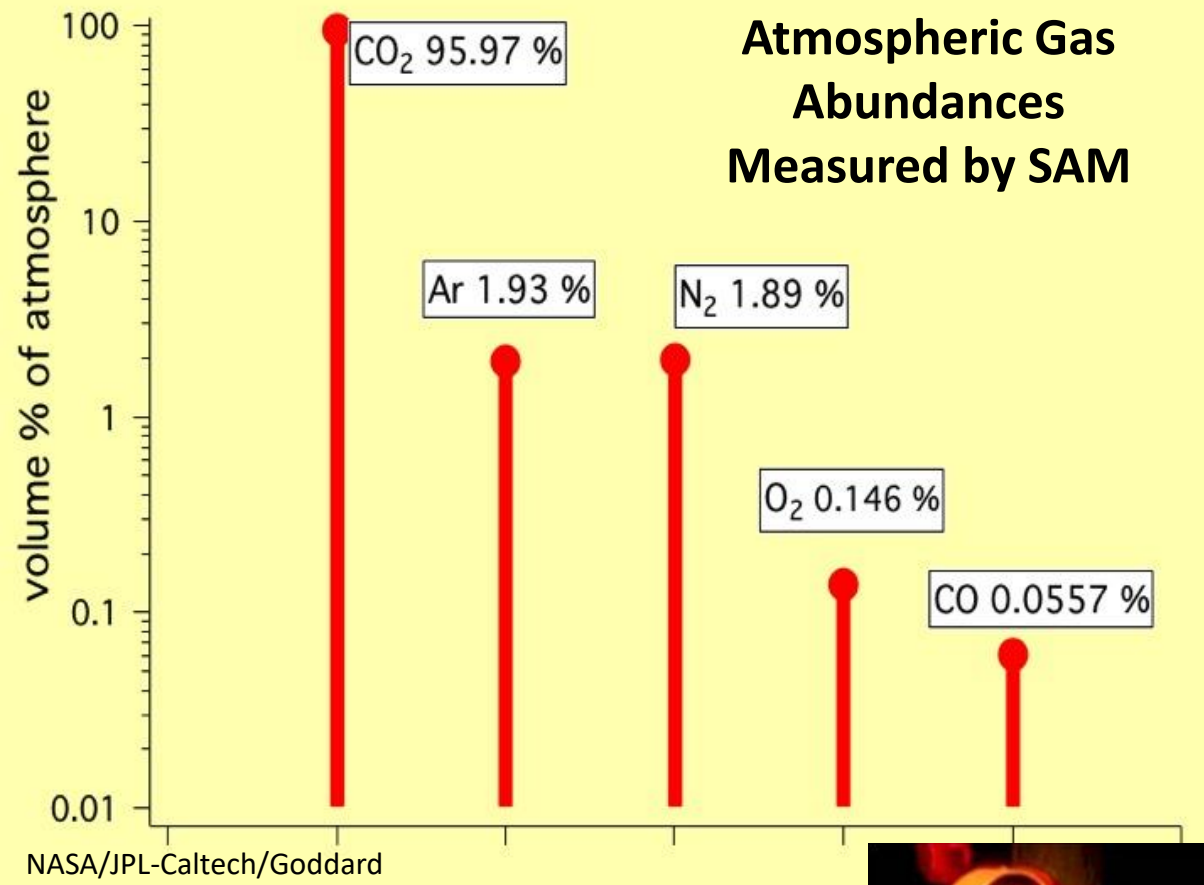
It heats soil and rock samples until they vaporize and then analyzes the resulting gases

CMU 2016

CheMin Inlet



CheMin uses X-rays to determine mineral content and crystal structure of surface samples



SAM found that argon, rather than nitrogen is the second most abundant gas

SAM also found that Mars' atmosphere is enriched in the heavy versions of isotopes, indicating massive atmospheric loss to space

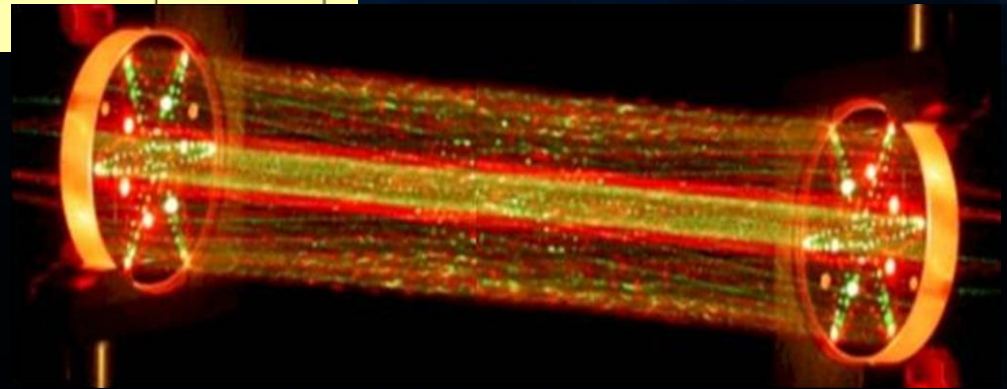
$$\delta^{13}\text{C} = 46 \pm 4 \text{ per mil}$$

$$\delta\text{D} = 4950 \pm 1080 \text{ per mil}$$

$$^{40}\text{Ar}/^{36}\text{Ar} = 1900 \pm 300$$

Methane has not been definitively detected

Upper limit = 1.3 ppb

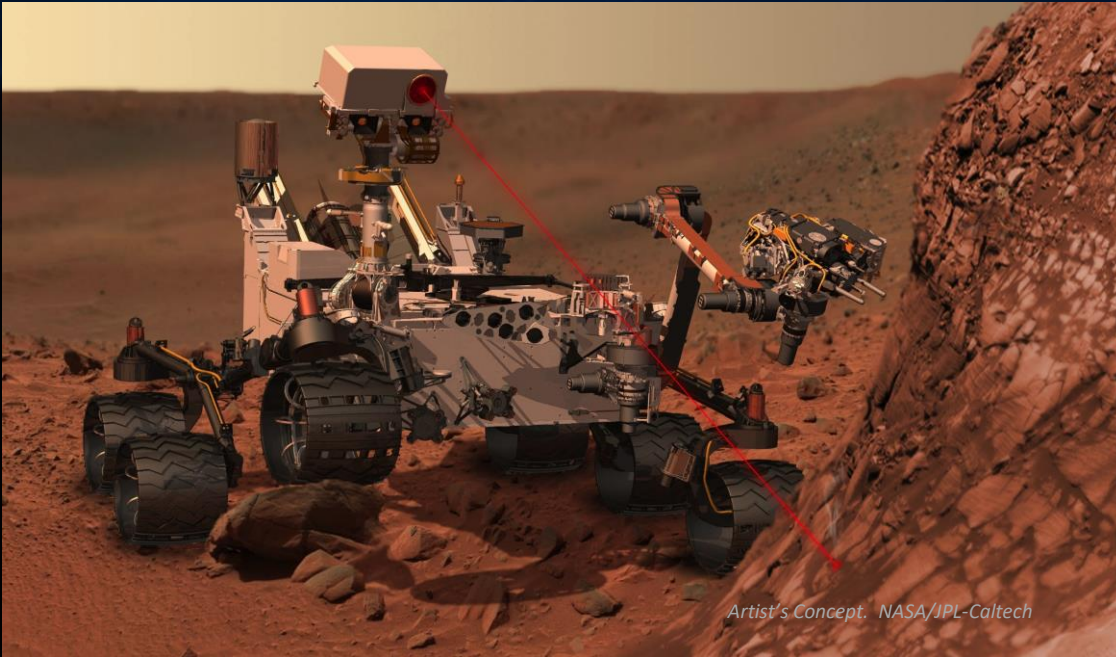


The SAM Tunable Laser Spectrometer and Mass Spectrometer measure atmospheric composition

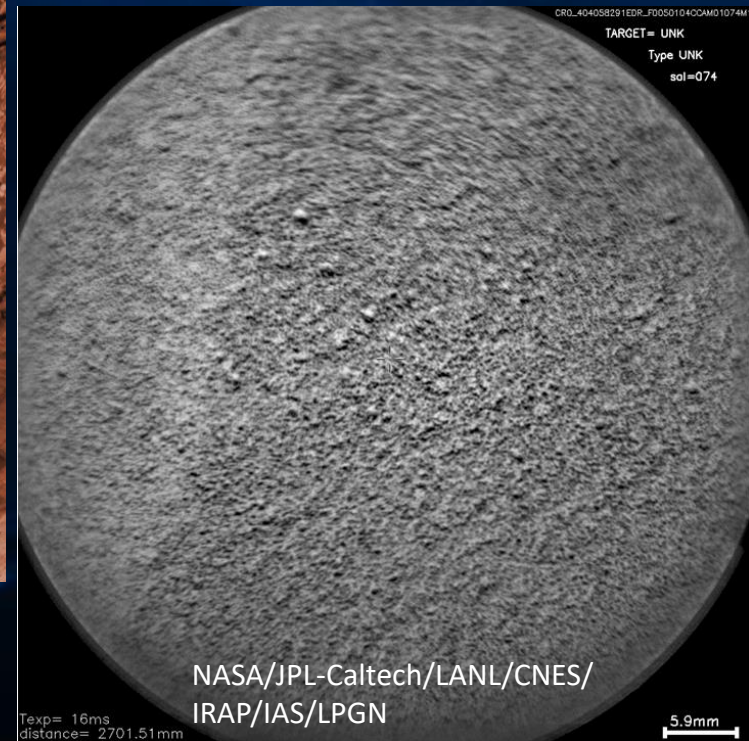
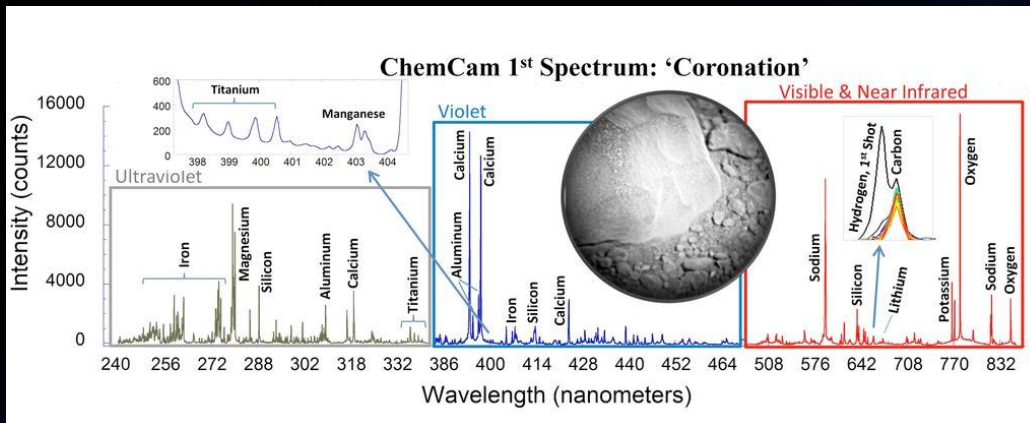
EMC 2016



A Laser (ChemCam)



Artist's Concept. NASA/JPL-Caltech



NASA/JPL-Caltech/LANL/CNES/
IRAP/IAS/LPGN



NASA/JPL-Caltech/MSSS



John Klein dime-sized drill hole with light-toned veins and ChemCam profile

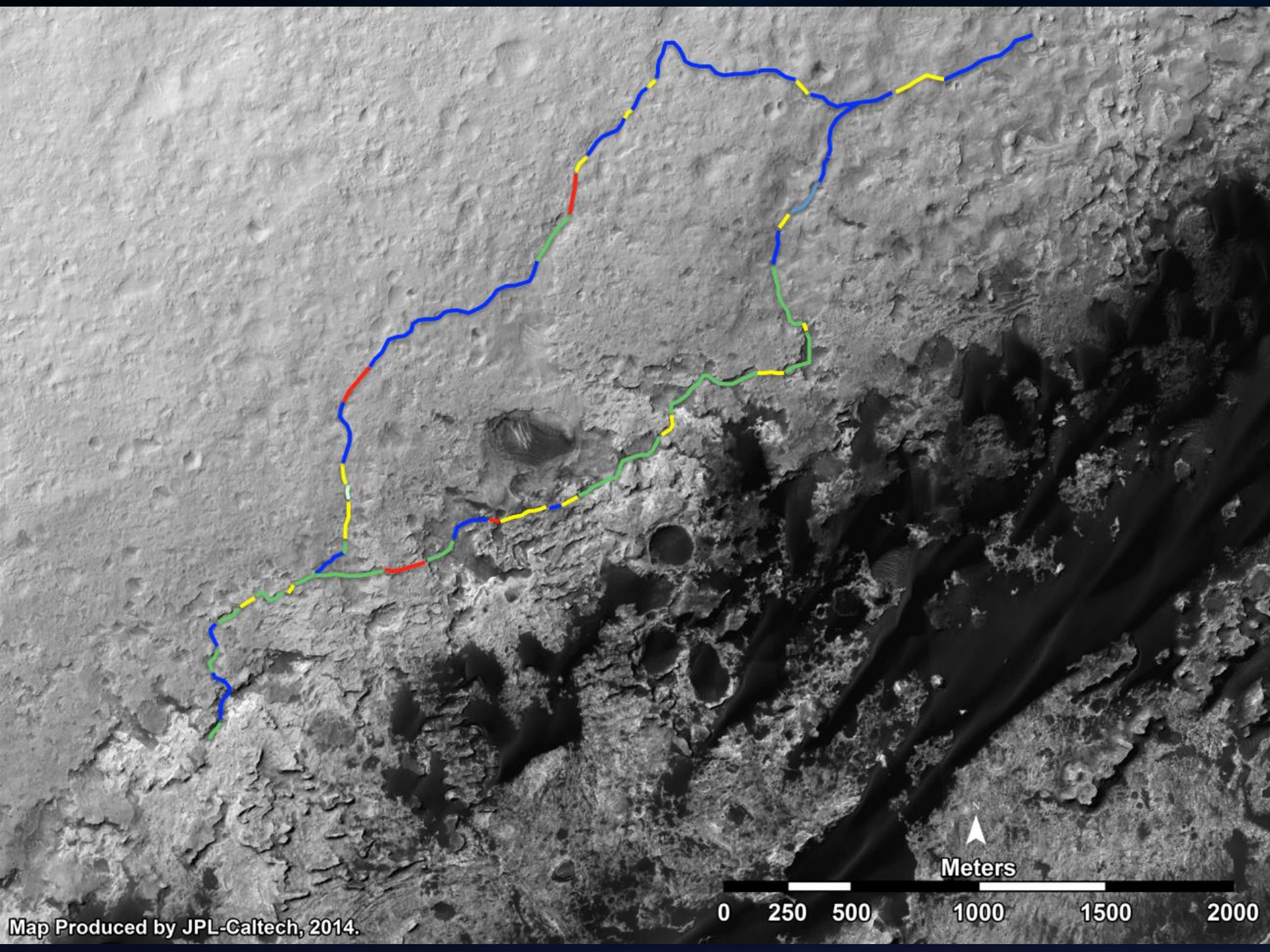
An Ancient Habitable Environment at Yellowknife Bay

- **The regional geology and fine-grained rock suggest that the John Klein site was at the end of an ancient river system or within an intermittently wet lake bed**
- **The mineralogy indicates sustained interaction with liquid water that was not too acidic or alkaline, and low salinity. Further, conditions were not strongly oxidizing.**
- **Key chemical ingredients for life are present, such as carbon, hydrogen, oxygen, phosphorus, and sulfur**
- **The presence of minerals in various states of oxidation would provide a source of energy for primitive organisms**



WDC? The Future

Artist's Concept. NASA/JPL-Caltech





The Road Ahead

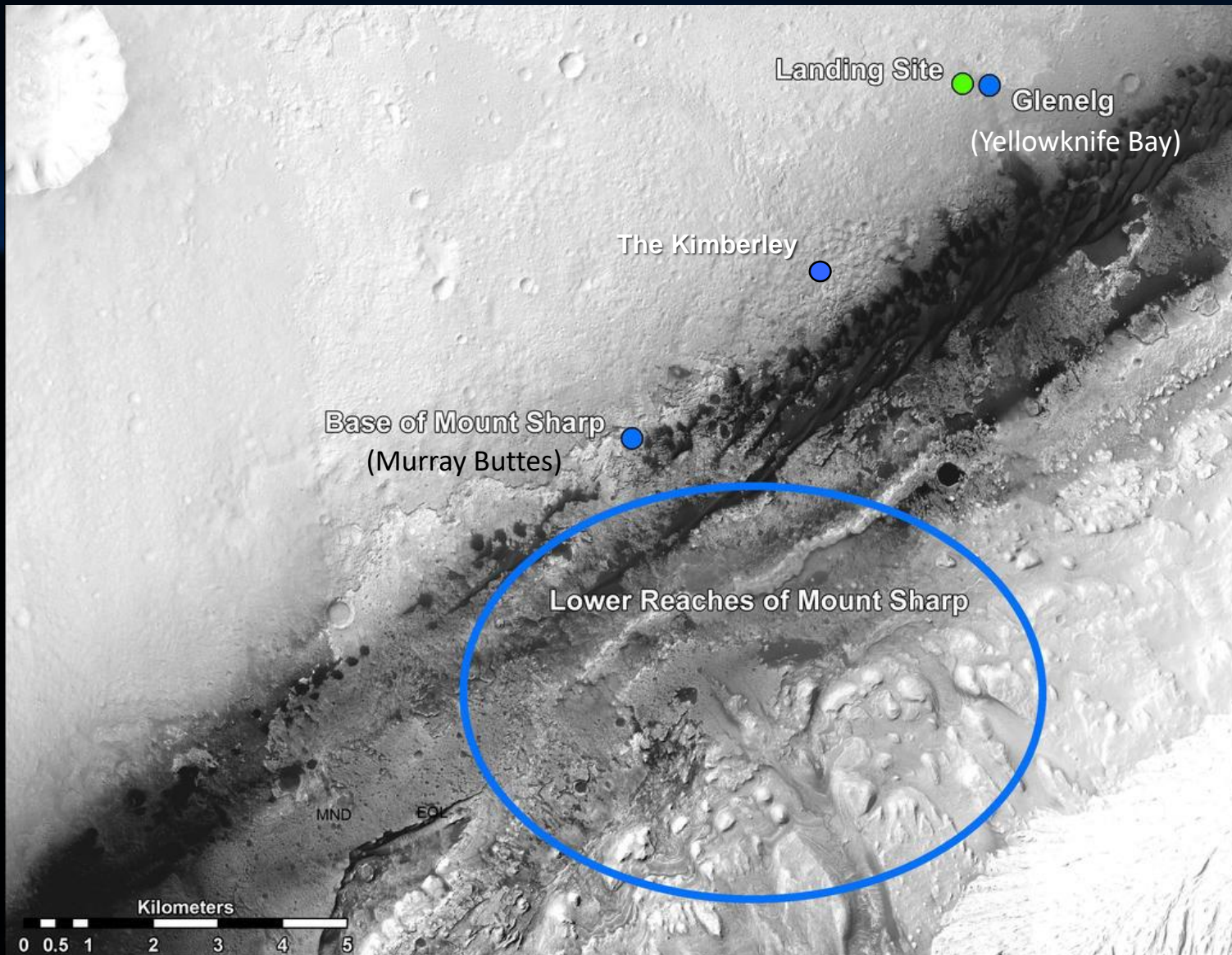




Targets for Exploration



NASA/JPL-Caltech/MSSS



NASA/JPL-Caltech/Univ. of Arizona

Curiosity's ultimate goal is to explore the lower reaches of the 5-km high Mt. Sharp

